United States
Department of
Agriculture

Forest Service

**Southern
Research Station**

General Technical
Report SRS–71

Proceedings of the 12th Biennial Southern Silvicultural Research Conference

Biloxi, Mississippi
February 24–28, 2003

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January 2004

Southern Research Station
P.O. Box 2680
Asheville, NC 28802

Proceedings of the 12th Biennial Southern Silvicultural Research Conference

Edited by
Kristina F. Connor

Biloxi, Mississippi
February 24-28, 2003

Hosted by
Mississippi State University, Department of Forestry
USDA Forest Service, Southern Research Station

Sponsored by
Mississippi State University, Department of Forestry
National Association of Consulting Foresters of America
National Association of Professional Forestry Schools and Colleges
National Hardwood Lumber Association
Society of American Foresters
Southern Industrial Forest Research Council
USDA Forest Service, Southern Research Station

Published by
USDA Forest Service
Southern Research Station
Asheville, North Carolina
January 2004

PREFACE

The 12th Biennial Southern Silvicultural Research Conference was held February 24-28, 2003, at the Beau Rivage Resort and Casino in Biloxi, MS. This conference was the latest in a series of meetings designed to provide a forum for the exchange of research information among silviculturists and researchers. Presentations emphasized research in wildlife ecology; fire ecology; natural pine management; forest health; growth and yield; upland hardwoods – natural regeneration; hardwood intermediate treatments; longleaf pine; pine-plantation silviculture; site amelioration and productivity; pine nutrition; pine planting, stocking, and spacing; ecophysiology; and bottomland hardwoods – natural and artificial regeneration. Field trips included visits to (1) the DeSoto National Forest to observe longleaf pine silvicultural practices and (2) the Sandhill Crane Refuge, the University of Southern Mississippi's Gulf Coast Research Laboratory, and the USDA Forest Service Laboratory at Saucier, MS, to observe current research efforts. Altogether, 338 people attended; 110 gave oral presentations, and 59 presented posters. Douglas P. Richards, Associate Director, Mississippi State University, Forest and Wildlife Research Center and Nancy Herbert, Assistant Director, USDA Forest Service, Southern Research Station, gave the welcoming remarks.

Conference sponsors included Mississippi State University, Department of Forestry, Forest and Wildlife Research Center; National Association of Consulting Foresters of America; National Association of Professional Forestry Schools and Colleges; National Hardwood Lumber Association; Society of American Foresters; Southern Industrial Forest Research Council; and the USDA Forest Service, Southern Research Station. The conference steering committee worked many hours to review abstracts, establish a program for oral and poster presentations, and make all necessary logistical arrangements. Steering committee members included:

Andrew Ezell (Local Arrangements Chair)
Mississippi State University, Department of Forestry, Mississippi State, MS
Susan Fox (Conference Chair)
USDA Forest Service, Southern Research Station, Asheville, NC
Kenneth Outcalt (Past Program Chair; Poster Session)
USDA Forest Service, Southern Research Station, Athens, GA
Dave Haywood (Meeting Announcements)
USDA Forest Service, Southern Research Station, Pineville, LA
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USDA Forest Service, National Forest System, Atlanta, GA
Brian Lockhart (Student Awards Judging Coordinator and Meeting Evaluation; Audio/Visual)
USDA Forest Service, Southern Research Station, Stoneville, MS
James Guldin (Moderator Selection)
USDA Forest Service, Southern Research Station, Monticello, AR
Gordon Holley (Audio/Visual)
Oklahoma State University, Stillwater, OK
Brian Oswald (Moderator Selection)
Steven F. Austin State University, Nacogdoches, TX
John Adams (Meeting Announcements)
Louisiana Tech, Monroe, LA

Partial funding for the conference was provided by the Southern Research Station and Mississippi State University. We gratefully acknowledge Mississippi State University's Department of Forestry for handling fiscal matters, hotel arrangements, and registration. Special thanks to both Ken Outcalt and Dave Haywood, past chairs of the meeting, for invaluable advice; to Lynne Breland for coordinating communications among the Forest Service, Mississippi State University, and the hotel; to Patricia Outcalt for creating and updating the conference Web page; to Jillian Donahoo for tracking abstracts and manuscripts; and to the Mississippi State University students who helped with transportation, set up posterboards, and helped with registration. The many people who contributed to the success of the field trips have our sincere thanks. We also gratefully acknowledge all those who helped judge student presentations and posters.

Special recognition is given to the moderators. They were: Nancy Herbert, Hermann Gucinski, John Adams, Ken Outcalt, Don Bragg, John Rennie, Dave Loftis, Brian Lockhart, Dean Gjerstad, Bruce Jewell, Phil Dougherty, Hans Williams, Jimmie Yeiser, Jim Chambers, Norman Davis, and Emile Gardiner.

Papers published in this volume were submitted by the authors in electronic media. Limited editing was done to ensure a consistent format. Authors are responsible for content and accuracy of their individual papers.

Kristina F. Connor
Program Chair
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Wildlife Ecology

Moderator:

NANCY HERBERT
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VEGETATION COVER AFFECTS MAMMAL HERBIVORY ON PLANTED OAKS AND SUCCESS OF REFORESTING MISSOURI RIVER BOTTOMLAND FIELDS

Shannon Dugger, Daniel C. Dey, and Joshua J. Millspaugh[1]

Abstract—We are evaluating oak regeneration methods at Plowboy Bend and Smoky Waters Conservation Areas in the Missouri River floodplain by planting oak seedlings in different cover types (redtop grass vs. natural vegetation) on four 40-acre fields. After 1 year, survival of planted oaks was high; however, herbivory from rabbits was intense depending on cover type. Damage to an individual oak seedling was substantially more severe in the natural vegetation fields than in the redtop grass fields. Most herbivory in the redtop grass fields occurred near the field edges, whereas herbivory occurred throughout the natural vegetation fields. In the winter of 2001-2002, we estimated rabbit densities at one rabbit per acre in the redtop grass field and three rabbits per acre in the natural vegetation field based on a mark-recapture study at Plowboy Bend. We attribute these differences in rabbit density, and severity and extent of damage to oak seedlings, to composition and structure of the ground flora (cover type), which may influence food availability and predation risk to rabbits.

INTRODUCTION

Managers are interested in planting oaks in the Mississippi River and Lower Missouri River floodplains for a variety of reasons including afforesting former agricultural bottomlands, conserving native bottomland tree species, improving wildlife habitat, and establishing agroforestry practices. However, regenerating oaks in bottomland fields can be difficult due to intense competition from other vegetation and to wildlife damage. We initiated a study to evaluate different methods for establishing bottomland oaks in floodplains using different nursery seedling types and planting seedlings with a cover crop of redtop grass (*Agrostis gigantea* Roth) to control competition (Dey and others 2003, Shaw and others 2003). After the first growing season, we observed a substantial amount of rabbit herbivory on the planted oak seedlings. This varied by cover crop within the fields.

The eastern cottontail rabbit (*Sylvilagus floridanus*) is a habitat generalist with an extensive geographic range that covers the eastern two-thirds of the United States (Conway and others 1974, Hanson and others 1969, Lord 1963). Rabbits are herbivores that prefer succulent green vegetation. In Missouri, the most preferred foods are blue grass (*Poa pratensis* L.), wheat (*Triticum aestivum* L.), and white clover (*Trifolium repens* L.) when they are available. In the winter, the rabbit's diet includes more buds, bark, shoots and twigs of vines, shrubs, and trees, especially when the ground is snow covered (Haugen 1942, Schwartz and Schwartz 1995). During the summer, rabbit damage to woody plants is minimal because of the abundance of preferred grasses, legumes, and forbs. But in winter, rabbits can cause severe damage to tree reproduction by pruning, barking, and girdling stems and shoots, which often increases seedling mortality (Geis 1954, Meiners and Martinkovic 2001). Trees with thin bark, young stump sprouts, and seedlings are particularly vulnerable.

The specific objectives of this paper are to estimate the winter population density of rabbits by cover type within the 40 acre fields at Plowboy Bend Conservation Area, MO, and to relate population density to the amount and distribution of rabbit herbivory on planted oak seedlings by cover type. The two cover types in this study are redtop grass and natural vegetation, in which we have planted oak seedlings.

METHODS

The study was located on two conservation areas managed by the Missouri Department of Conservation: Smoky Waters (Sec. 5, T 44 N, R 9 W and Sec. 1, T 44 N, R 10 W; Cole County) and Plowboy Bend (Secs. 24 and 25, T 47 N, R 14 W; Moniteau County). Shaw and others (2003) have reported the experimental design of this study and how the vegetation data were collected. To summarize, we planted swamp white oak (*Quercus bicolor* Willd.) and pin oak (*Quercus palustris* Muenchh.) seedlings grown as 1-0 bareroot, 3 gallon RPM™, or 5 gallon RPM™. Grossman and others (2003) have described the Root Production Method (RPM™) that was developed by Forrest Keeling Nursery in Elsberry, MO, and used to grow the RPM™ seedlings in our study. The RPM™ is a cultural system that uses air root pruning to produce a large container-grown seedling with a dense, fibrous root system. We planted the oak seedlings in 40-acre fields with a cover crop of redtop grass, or with natural vegetation that develops when bottomland crop fields are abandoned. Within each field seedlings were planted at a density of 48 trees per acre (30 foot by 30 foot spacing).

Initial seedling sizes after planting are shown in table 1. Heights and basal diameters were similar between the two RPM™ stock types for each oak species. Height averaged 7.2 feet and 7.6 feet for pin oak 3 gallon RPM™ and 5 gallon RPM™ trees, respectively. Regardless of RPM™

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Table 1—Height and basal diameter (1 inch above groundline) of seedlings planted in this study

Species and stock type	Sample size	Mean basal diameter	Mean total height
	no. trees	*- - inches - -*	*- - feet - -*
Pin oak bareroot	1,175	0.23 ± 0.05	1.1 ± 0.2
Pin oak 3 gallon	1,204	0.75 ± 0.13	7.2 ± 1.2
Pin oak 5 gallon	1,269	0.79 ± 0.14	7.6 ± 1.2
Swamp white oak bareroot	1,192	0.25 ± 0.06	1.1 ± 0.2
Swamp white oak 3 gallon	1,274	0.66 ± 0.13	5.8 ± 1.1
Swamp white oak 5 gallon	1,248	0.66 ± 0.13	6.1 ± 1.1

stock type, pin oak seedlings averaged 0.8 inches in basal diameter (1 inch above the root collar). Swamp white oak RPM™ seedlings were slightly smaller in height and basal diameter than the pin oaks. In contrast, bareroot seedlings averaged about 1.1 feet in height and 0.2 inches in basal diameter, regardless of species. Annually, we monitored survival, diameter and height growth, and animal damage on the planted oaks.

From June through August of 2000, ground layer vegetation was monitored using 432 1-m^2 quadrats that were randomly located across all 40-acre cover type fields. Percent ground cover by species was determined on the quadrats. Vertical structure of the ground flora was quantified at each quadrat location by setting a density board between rows of trees to estimate percent cover of grasses, woody vegetation, forbs, and total vegetation by 0.8 foot height increments up to a height of 6.6 feet (Hays and others 1981).

Beginning in the fall of 2000 and through the winter, we noticed that cottontail rabbits (*Sylvilagus floridanus*) were browsing a substantial number of the planted oaks, especially in the natural vegetation fields. Therefore, in the spring of 2001 we documented the herbivory damage by recording the proportion of each RPM™ seedling stem that was girdled; i.e., where the rabbits had chewed through the bark and eaten the cambium. For bareroot seedlings, we noted if the stem was completely clipped or not.

In December 2001, we set Tomahawk cat/rabbit model 606 live-traps at a rate of one per acre in each of the two 40-acre cover type fields to estimate population density of cottontail rabbits at Plowboy Bend Conservation Area. We set traps on a 210 foot by 150 foot grid in the natural vegetation field for 8 continuous days, then repeated the procedure for another 8 consecutive days in the redtop grass field.

We covered the traps with black roofing paper to minimize stress on the rabbits and to protect them from inclement weather. The roofing paper was tightly wrapped around the trap and held in place by the weight of the trap. We left the ends of the trap uncovered so the food was visible to the rabbits and so they could get into the trap. We baited the traps with equal amounts of cabbage, carrots, celery, and rabbit feed. We checked each trap daily between 7:00 a.m. and 9:00 a.m. for captures and re-baited them as needed.

Initially, each rabbit caught was assigned a unique number and marked with a pair of similarly numbered metal tags that we attached to each ear. We measured the rabbit's weight, determined its sex, and rated its health based on the visual appearance and behavior of the animal. Each day of the 8 day trapping session, we recorded the ear tag number of recaptured marked rabbits and released them from the point of capture. Newly captured rabbits were marked with uniquely numbered ear tags and measured. We treated all injuries sustained by the rabbits during the trapping process with an antiseptic spray.

We determined rabbit abundance using the Schnabel method for mark and recapture data. The Schnabel method is suitable for multiple trapping periods, and accounts for possible deaths and rabbits that are captured more than once. The standard Schnabel equation for determining a population estimate is:

$$N = \frac{\sum_t (C_t M_t)}{\sum_t R_t}$$

where, N is the population estimate, C_t is the total number of individuals caught in sample t, M_t is the number of marked individuals in the population just before sample t is taken, and R_t is the number of individuals already marked when caught in sample t.

RESULTS AND DISCUSSION

During the first summer, we identified 101 plant species in the redtop grass and natural vegetation fields at Plowboy Bend Conservation Area. Most plants were annual and biennial forbs and grasses of which slightly more than half were exotic species. Common native species included purslane speedwell (*Veronica peregrina* L.), cut-leaf primrose (*Oenothera laciniata* Hill), and horseweed (*Conyza canadensis* L.). Many species (N = 81) were not widely distributed, occurring on less than 10 percent of all the 1-m^2 quadrats. Woody species inventoried included boxelder (*Acer negundo* L.), eastern cottonwood (*Populus deltoides* Bartr. ex Marsh. var. *deltoides*), hackberry (*Celtis occidentalis* L.), and trumpet creeper (*Campsis radicans* L.). Total ground cover averaged 30 percent on the natural vegetation field, where the presence of grasses was minimal and forbs dominated the plant community. Sowing redtop grass as a cover crop increased the mean total ground cover to 53 percent and reduced the mean total cover of forbs to about 13 percent. Grasses dominated (75 percent of the total cover) the vegetation in the redtop grass field.

Vertical structure of the vegetation varied by cover treatment at Plowboy Bend Conservation Area (fig. 1). Vegetation grew to 4.9 feet on the natural vegetation field and 3.2 feet on the redtop grass field. Percent cover decreased more rapidly with increasing height above the ground on the redtop grass field than on the natural

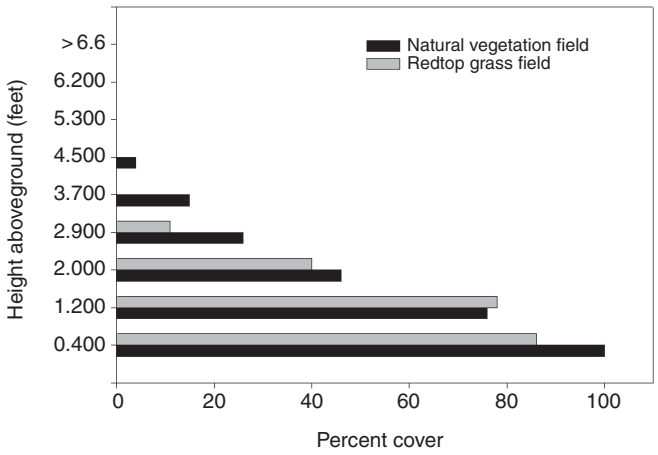

Figure 1—Height of vegetation and percent cover by height class in the redtop grass and natural vegetation fields after 1 year at Plowboy Bend Conservation Area.

vegetation field. At about 3 feet above the ground, total vegetation cover had dropped to 12 percent on the redtop grass field, but there was still 25 percent cover on the natural vegetation field. Total plant cover on the natural vegetation field averaged 4 percent even at 4.5 feet.

First-year (fall 2000) survival of oak reproduction at Plowboy Bend Conservation Area was high for both RPMTM and bareroot seedlings, regardless of species or cover type. Survival of RPM™ was nearly 100 percent, while that of bareroot seedlings averaged 82 percent for pin oak and 92 percent for swamp white oak. Second-year survival (fall 2001; i.e., 1 year after the first rabbit herbivory) for RPM™ seedlings remained high, but it declined for bareroot stock, regardless of species. Swamp white oak bareroot seedling survival was 73 percent in the redtop grass field and 80 percent in the natural vegetation. Survival was lowest for pin oak bareroot seedlings with only 53 percent of the seedlings surviving in the natural vegetation field and 67 percent in the redtop grass field.

Second-year heights of oak seedlings were reduced in the natural vegetation field at Plowboy Bend Conservation Area, where RPM™ trees lost significant amounts of height due to shoot dieback and resprouting after being girdled by rabbits (table 2). In contrast, there was generally a net increase in height after 2 years in the redtop grass field, regardless of species and stock type.

Herbivory to oak seedlings primarily consisted of barking, girdling and shoot clipping by rabbits. Damage to planted oaks was substantially greater in the natural vegetation field than the redtop grass field. In the redtop grass field, 69 percent of the bareroot seedlings had no rabbit herbivory damage and approximately one-third had the main stem clipped. In contrast, 85 percent of bareroot seedlings were clipped in the natural vegetation field. Of the RPM™ seedlings in the natural vegetation field, 97 percent were girdled or had the main stem completely clipped, whereas only 25 percent were damaged in the redtop grass field (fig. 2). Rabbit damage was severe (> 50 percent of the main stem girdled or shoot clipped) on 87 percent of the RPM™ seedlings in the natural vegetation field, but only 14 percent of the damage was severe in the redtop grass field. Most herbivory in the redtop grass field occurred near the field edges, whereas herbivory occurred throughout the natural vegetation field.

We marked a total of 26 rabbits in the redtop grass field and 58 rabbits in the natural vegetation field in 8 days of trapping. When incorporating recapture rates, we estimated rabbit densities at roughly one rabbit per acre and three rabbits per acre in the redtop grass and natural vegetation fields, respectively. Rabbit densities were high in the natural vegetation field compared to densities reported in the literature for the Midwestern United States (Swihart and Yahner 1982). We believe that the higher density of rabbits in the natural vegetation field is because the growth of summer vegetation provides good winter hiding cover for the rabbits, thus reducing their risk to predation. The preponderance of residual vegetative cover offers refugia to rabbits, thus attracting them to these sites. As a result, rabbits may be more likely to feed around these suitable cover sites.

Redtop grass sod is effective in preventing the development of natural vegetation in former bottomland crop fields. In the winter, the low-growing (< 2 feet in summer) redtop grass mats down and provides little cover

Table 2—Average initial and second-year height by species, stock type and cover type at Plowboy Bend Conservation Area

Species and stock type	Natural vegetation field		Redtop grass field	
	Initial height	Second-year height	Initial height	Second-year height
	feet			
Pin oak bareroot	1.1	0.5	1.1	1.0
Pin oak RPM™	7.5	4.8	7.8	8.2
Swamp white oak bareroot	1.1	0.9	1.2	1.4
Swamp white oak RPM™	6.0	2.7	6.1	6.3

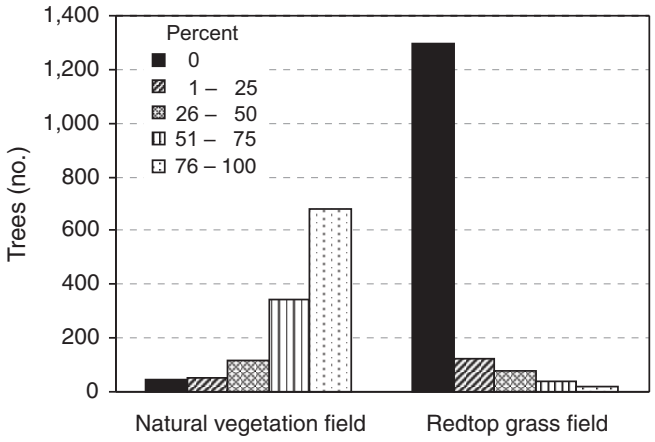

Figure 2—Distribution of RPM™ seedlings by rabbit herbivory damage class after the winter of 2000-2001 in the redtop grass and natural vegetation fields at Plowboy Bend Conservation Area. Damage classes are the percent surface area of each seedling stem girdled or injured by rabbits.

for rabbits. In contrast, vertical cover in the natural vegetation field remains relatively dense with increasing height above the ground because many of the forbs are heavy-stalked, woody-stemmed species such as horseweed, common sunflower (*Helianthus annuus* L.), and common lambs quarter (*Chenopodium album* L.) that do not readily mat down during the winter. In the natural vegetation field, winter cover is present to at least 3 feet high. The higher rabbit densities in the natural vegetation field are associated with more extensive and severe herbivory damage to the planted oak seedlings. In addition, food availability in the winter is limited in either of the redtop grass or natural vegetation fields, making the oak seedlings more vulnerable to rabbit herbivory.

Methods that create favorable understory conditions for rabbits may hamper regeneration efforts. We found that even subtle differences in vegetation structure are important determinants of rabbit density and herbivore damage to tree seedlings. Through manipulation of the habitat, managers can control rabbit damage to oak reproduction. Redtop grass cover is not good rabbit habitat in the winter, and planted seedlings are more likely to survive the winter with little herbivory damage from rabbits. Larger fields of redtop grass will have proportionally less rabbit herbivory because there is less edge to field area than in smaller fields. Fall mowing of natural vegetation in bottomland tree plantings to eliminate winter cover may be an alternative to using redtop grass as a cover, but this needs to be evaluated in future studies. Using radiotelemetry, our future work will evaluate fine scale rabbit use of planted fields, and we will relate this to habitat use and damage to planted oak seedlings.

ACKNOWLEDGMENTS

This work was funded through the University of Missouri Center for Agroforestry under cooperative agreements AG-02100251 with the U.S. Department of Agriculture, Agriculture Research Station (ARS) and C R 826704-01-0 with the U.S. Environmental Protection Agency (EPA). The results presented are the sole responsibility of the authors and may not represent the policies or positions of the ARS or EPA. This research was approved by the University of Missouri Animal Care and Use Committee (Protocol #3820).

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RELATIONSHIPS BETWEEN HERPETOFAUNAL COMMUNITY STRUCTURE AND VARYING LEVELS OF OVERSTORY TREE RETENTION IN NORTHERN ALABAMA: FIRST-YEAR RESULTS

Zachary I. Felix, Yong Wang, and Callie Jo Schweitzer[1]

Abstract—Forest managers are increasingly considering the effects their decisions have on the biodiversity of an area. However, there is often a lack of data upon which to evaluate these decisions. We conducted research to examine the relationship between silvicultural techniques, particularly shelterwood cuts with varying levels of basal area retention, and the community structure of amphibians and reptiles in the Cumberland Plateau of northern Alabama. We have implemented five levels of basal area retention at 15 plots (4 ha per site): 0 percent, 25 percent, 50 percent, 75 percent, and control (100 percent) with three replicates each. Drift fences with pitfall and funnel traps, and coverboards were used to quantify herpetofauna at each site. We predicted that plots with high basal area would provide better conditions for amphibians, sites with low basal area would be more favorable for reptiles, and sites with intermediate basal area would contain the most structurally and climatically complex habitats, and thus the highest species richness of herpetofauna. Our research will provide both a theoretical framework furthering our understanding of factors affecting the distribution and abundance of these organisms and applicable data that may be used to assist forest managers in sustaining these communities.

INTRODUCTION

Forest managers are increasingly asked to consider the conservation of biodiversity in their stewardship responsibilities. For this to be effective, managers must be given choices when it comes to the silvicultural techniques they use. This may include the use of alternatives to clearcuts such as shelterwoods or two-aged harvests. It is believed that these systems, because they leave some live trees standing, have a less dramatic impact on wildlife and their habitat than clearcutting. However, little is known about the benefits, if any, these alternatives provide to wildlife.

One group of wildlife that is increasingly considered in forest management decisions is herpetofauna, including all species of reptiles and amphibians. Because these organisms are ectothermic, they are very efficient at producing new tissue and, as a result, comprise a large portion of vertebrate biomass in forest ecosystems. For example, in North Carolina, terrestrial salamanders alone can reach densities of 18,000 per ha and biomass of over 16 kg per ha (Petranka and Murray 2001). Wyman (1998) demonstrated that by reducing invertebrate numbers, salamanders can reduce decomposition rates of forest litter by up to 17 percent, arguably impacting carbon dynamics of forest ecosystems. Some terrestrial turtles have been implicated as vectors of seed dispersal (Gibbons 1988). Snakes can have effects on control of rodent populations (Fitch 1949). Rodents, in turn, are capable of impacting plant community structure (Hayward and Phillipson 1979). These examples highlight the importance of herpetofauna in ecosystems, and show that it is plausible that they indirectly alter forest processes such as regeneration and nutrient cycling.

The preliminary data reported here were collected in the first of a 4-year study. This study is taking place in conjunction with research on upland oak regeneration (Schweitzer, in press) and avian response to treatments (Lesak and others, in press). The objectives of this research were (1) to compare herpetofaunal communities among treatments with a spectrum of tree retention levels and (2) to determine if differences existed in the habitats among treatments, in terms of the climate and the physical structure.

STUDY AREA

The study took place in the Cumberland Plateau region of Jackson County, which is in northeastern Alabama. Study sites are upland forests dominated by oaks (*Quercus* spp.), hickories (*Carya* spp.), yellow poplar (*Liriodendron tulipifera* L.), and sugar maple (*Acer saccharum* Marsh.). Soils are composed of gravelly and stony loams, and slopes average between 12 and 20 percent.

The study followed a randomized complete block design with three blocked replicates of five treatments involving varying levels of basal area retention of trees. Treatment categories included clearcuts, 25, 50, and 75 percent retention, and controls. The clearcuts, 25 percent, and 50 percent retention treatments were chainsaw-felled in a commercial logging operation. In 75 percent retention treatment plots, the midstory was removed by incising trees and applying the herbicide Arsenal (active ingredient imazapyr) into the cut area to achieve a shelterwood cut. Two blocks were located on a north-facing slope at Jack Gap, and the other at Miller Mountain on a southwest-facing slope. Each individual experimental unit was 4 ha in size.

METHODS

Habitat Sampling

Climate—Climatic regimes were sampled with H8 Hobo dataloggers (Onset Corp., Bourne, MA). One datalogger was placed adjacent to each drift fence during trapping

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

periods and recorded hourly air temperature (°C), soil temperature (°C) at 7 cm below the surface, and relative humidity (percent).

Physical—Two 10-m line transects were utilized at each drift fence to sample physical attributes of habitat. The point-intersect method was used to calculate percent cover of the following variables along each transect: leaf litter, bare soil, herbaceous vegetation, woody vegetation, slash, rocks, and coarse woody debris. Every 2 m along transects, percent canopy closure was measured with a hand-held spherical densiometer, and leaf litter depth was measured with a ruler.

Herpetofaunal Sampling

The main method used to sample reptiles and amphibians was drift fence trapping. Drift fences were 15 m in length, constructed of silt fencing, and included one 19-L pitfall bucket at each end and two double-sided funnel traps placed on either side of fences at the midpoint. Three drift fences were placed on each plot (9 per treatment, 45 total). Drift fences were opened for a total of 300 trap nights in August and September 2002, and February 2003. A trap night was defined as one drift fence open for 24 hours. Artificial cover objects, or coverboards, were also used for animal sampling (Fellers and Drost 1994). Small coverboards (30 x 20 cm) were used to target salamanders (90 per plot), while larger (120 x 60 cm) boards were used for both reptiles and amphibians (9 per plot). Community comparisons were made in terms of relative abundance and species richness.

Statistical Analyses

Randomized complete block ANOVA tests were used for comparisons among treatments. Tests on both temperature and relative humidity measurements were performed on means of 18 days of hourly measures taken in August and September of 2002. Mean separations were performed using Tukey's HSD test. Significance is reported at a level of $p < 0.05$. Data transformations included arcsine transformation of percentage data associated with relative humidity and ground cover measures.

RESULTS

Climate—Both air ($F_{4,8} = 28.26$, $P = 0.002$) and soil ($F_{4,8} = 31.23$, $P < 0.005$) temperatures were different among treatments (table 1). Temperatures were higher on clearcuts and 25 percent retention plots, and lower on 50 percent, 75 percent, and control plots. Relative humidity was also different among treatments ($F_{4,8} = 20.9$, $P < 0.005$), with higher values on control and 75 percent treatments and lower values on 50 and 25 percent, and clearcuts.

Physical—Canopy cover differed among treatments ($F_{4,8} = 105.3$, $P < 0.005$, table 1). Canopy cover was higher on control and 75 percent treatments, intermediate on 25 and 50 percent, and lower on clearcuts. Mean litter depth also differed among treatments ($F_{4,8} = 11.27$, $P < 0.005$), with greater depths on controls and lower depths on 50 percent, 25 percent, and clearcut treatments. Four of the seven categories of ground cover measured differed among treatments (figs. 1 and 2). Leaf litter cover was higher on controls and lower on clearcuts ($F_{4,8} = 11.27$, $P < 0.005$). Residual slash cover showed the opposite trend, with higher values on clearcuts and lower values on 75 percent and controls ($F_{4,8} = 35.21$, $P < 0.005$). Coarse woody debris cover was higher on clearcuts and lower in controls ($F_{4,8} = 6.54$, $P = 0.012$), and bare soil cover showed a similar pattern ($F_{4,8} = 11.22$, $P < 0.005$).

Animal captures—The most numerous group of reptile or amphibian captured was frogs and toads, with highest abundance in the 75 percent treatment (fig. 3). Captures of one species, the American toad (*Bufo americanus* Holbrook) made up a large percentage of this group. Lizard numbers were highest in 25 percent treatments, and snake captures peaked in clearcuts. Coverboard captures of salamanders were relatively low in numbers but showed the beginnings

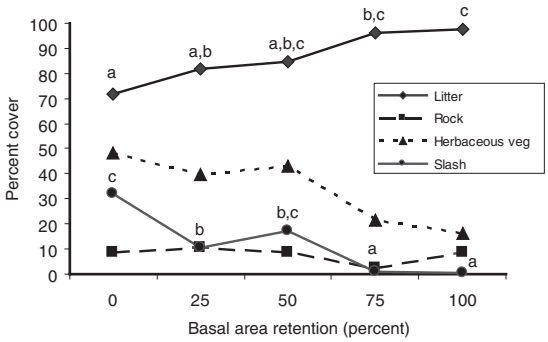

Figure 1—Percent ground cover of four variables across treatments in northern Alabama, August and September 2002.

Table 1—Mean environmental measures among various basal area retention treatments in northern Alabama, August and September 2002[a]

		Treatment (*percent BA retention*)			
Environmental variable	Clearcut	5	50	75	Control
Air temperature (°*C*)	26.7a	26.2a	25.8b	24.4b	24.2b
Soil temperature (°*C*)	25.9a	26.2a	25.8b	24.4b	24.2b
Relative humidity (*%*)	74.6a	76.1a	77.2a	80.8b	82.3b
Canopy cover (*%*)	14.1a	39.6b	48.7b	83.6c	89.6c
Litter depth (*cm*)	2.1a	2.7a	2.4a	3.4a,b	4.8c

BA = basal area.

[a] Means within rows with different superscripts are significantly different.

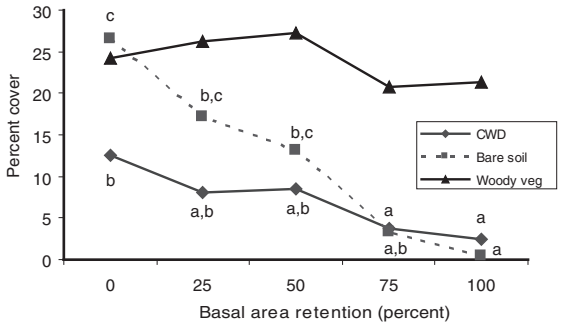

Figure 2—Percent ground cover of three variables across treatments in northern Alabama, August and September 2002.

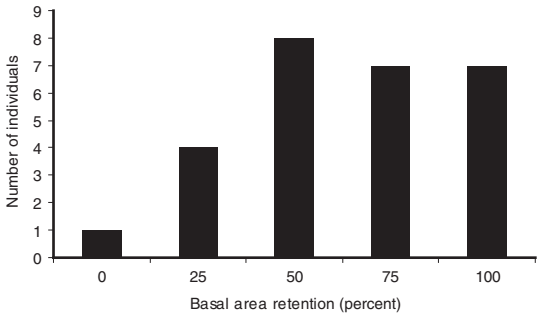

Figure 4—Captures of salamanders using artificial coverboards (1,485 boards) across treatments in northern Alabama, January 2003.

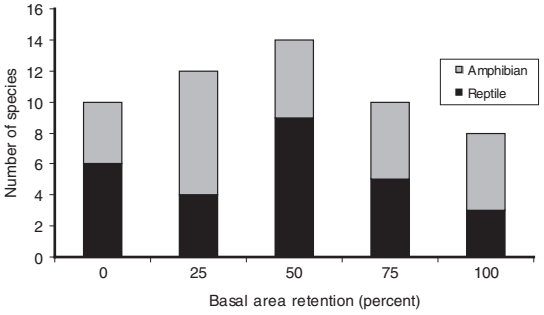

Figure 5—Species richness of reptiles and amphibians combined across treatments in northern Alabama, August and September 2002, and February 2003. Each bar represents the additive number of species of amphibians (hatched) and reptiles (solid) combined.

of a pattern with numbers maintained on the control, 75, and 50 percent treatments and dropping to a low on clearcuts (fig 4). Total species richness of reptiles and amphibians combined was highest on 50 percent treatments and tailed off towards clearcuts and controls (fig. 5).

DISCUSSION

Climate—Climatic conditions on clearcuts were warmer and drier than on the control area, with a gradient between the two extremes. Climate on clearcuts is characterized by warmer and more variable air temperatures and more variable relative humidity than forested sites (Chazal and Niewiarowski 1998, Gieger 1971). Another study found no difference in surface soil temperatures between clearcut and control areas (Phelps and Lancia 1995). It is interesting to note that air and soil temperatures and relative humidity were not different between the clearcuts and 25 percent treatments or between the control and 75 percent treatments. This suggests the amount of overstory canopy present may play an important role in regulating climate of a forest. For example, there was little difference between the 75 percent retention and control. The goal of the 75 percent treatment was to reduce the basal area by 25 percent without creating large canopy gaps using herbicide. Harpole and Haas (1999) found soil temperatures exhibited an increasing trend from control and herbicide treatments to two different shelterwood cuts, and peaked in clearcuts. The control and herbicide treatments were also the most similar in their study in terms of canopy cover and soil temperatures. These differences in climatic regimes will likely play an important role in determining the distribution and abundance of reptiles and amphibians on study plots.

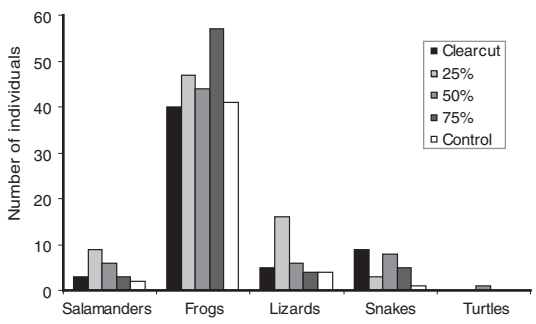

Figure 3—Captures of herpetofauna using drift fences for 300 trap nights across treatments in northern Alabama, August and September 2002, and February 2003.

Physical—The measured differences in percent canopy cover across treatments were as expected. It is notable that there was little difference in percent canopy cover measured between the 75 percent retention and controls. As discussed above, this was the goal of the treatment and the result is encouraging. Harpole and Haas (1999) also found similar canopy cover percentages between control stands and stands with understory removal via a herbicide treatment. Important components of herpetofaunal habitat, as indicated by measured ground cover categories, differed. These differing components included leaf litter, bare soil, coarse woody debris, and slash. Leaf litter coverage and depth are positively related to abundance of amphibians, especially salamanders (DeMaynadier and Hunter 1998, Pough and others 1987). Ash (1995) argued that decreases in litter depth and coverage after clearcutting may contribute to observed disappearances of salamanders. Greenberg and others (1994) found that certain species of lizards primarily use open-scrub habitat with a high proportion of bare soil. In Maine, high amounts of bare soil were negatively associated with capture rates of amphibians (DeMaynadier and Hunter 1998). Terrestrial amphibian abundance is positively associated with amount of coarse woody debris in the form of downed logs (Brooks 1999, Petranka and

others 1994, Ross and others 2000), especially logs in older states of decay (Butts and McComb 2000).

Animal captures—Trapping in the first year was limited due to equipment implementation efforts. Preliminary results suggested that most groups may be more abundant in intermediate treatments, but sample sizes are too low for any conclusions at this time. Salamander captures in drift fences were inconclusive. Drift fences were opened at the end of the summer, which is not the ideal time for targeting this group. Coverboard captures of salamanders were also low but suggested the beginnings of an interesting pattern. Abundance of salamanders seemed to be maintained in control, 75 percent, and 50 percent treatments but declined at the 25 percent level and were lowest in clearcuts. Some debate exists as to whether salamander abundances can be maintained in stands with intermediate harvest. Results of Harpole and Haas (1999) indicated populations of salamanders declined after even partial removal of canopy. Other research has found no difference in abundance between control stands and those stands with residual stocking ranging from 40 to 70 percent (Brooks 1999, Sattler and Reichenbach 1998). Observed patterns in species richness of reptiles and amphibians suggested that more species of herpetofuana were able to exist in plots with intermediate cuts. We predict this pattern will continue with additional trapping, and that it will be related to patterns of habitat complexity and heterogeneity.

ACKNOWLEDGMENTS

Research support was provided through the project "Sampling Amphibians and Reptiles in Northern Alabama" under Cooperative Agreement numbers 02-DG-11330134-097 dated May 1, 2002 through November 15, 2003, 02-CA-11330134-144 dated June 1, 2002 through December 31, 2003, and 03-DG-11330134051 dated January 1, 2003 through December 31, 2003. This research was supported by funds provided by the U.S. Department of Agriculture, Forest Service, Southern Research Station.

We thank the Southern Research Station of the U.S. Forest Service for financial and logistic support. The Plant and Soil Sciences Department at Alabama A&M University provided a graduate assistantship for ZIF. Thanks also to Mead Westvaco for assistance applying treatments and to all who helped with field work.

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SONGBIRD COMMUNITY VARIATION AMONG FIVE LEVELS OF OVERSTORY RETENTION IN NORTHERN ALABAMA

Adrian A. Lesak, Yong Wang, and Callie Jo Schweitzer[1]

Abstract—We compared songbird communities among varying degrees of overstory tree retention in the oak-hickory forest of the southern Mid-Cumberland Plateau region. Three 20-ha complete block replicates of 5 experimental treatments (15 treatment units, 4 ha per unit) were used. The five treatments were operational shelterwood stands with target overstory retention levels of approximately 0, 25, 50, 75, and 100 percent. The residual basal area and resultant canopy cover of these overstory retentions were compared among treatments and both showed three distinct conditions, closed canopy, open forest, and clearcut. Territory spot-mapping was used to quantify bird species richness and density during the first post-treatment year, between mid-April and July 2002. Sixty bird species were detected with 34 of those defending territories on the sites. Clearcuts (0 percent retention) had significantly lower values than the other four treatment types for overall bird territory density, species richness, and Shannon diversity index. Territorial density of breeding songbirds was highest in the 50 percent retention treatments, while species richness and Shannon diversity peaked in the units with 25 percent basal area retention.

INTRODUCTION

Songbirds in forested landscapes have shown population decreases in recent decades, creating widespread concern in the conservation community and an interest in their management and preservation (Ambuel and Temple 1982, Askins and others 1990, Robbins and others 1989). Anthropogenic habitat alteration has been widely suspected as a causal agent in these declines. A large proportion of existing forest songbird habitat is subject to some form of use or management, whether it is under governmental, industrial, or non-industrial private ownership. As a result, the motives and operations of forestry have a significant impact on the habitat of songbirds. Land managers often have conservation and management goals for their timber resources, but water, wildlife, and soil issues have increased in importance in a move toward a more holistic approach to ecosystem management. Ultimately, we would like the findings of our research to act as a guiding tool for land managers charged with the duty of balancing the myriad goals of forest stewardship in the southern Cumberland Plateau region.

The maintenance of forest bird populations is important for many reasons other than the valuable recreational and aesthetic qualities they bring to the forest ecosystems they inhabit. As the majority of forest songbirds are insectivorous, they provide a useful service to these systems and their resources by consuming a significant number of arthropods and their larvae, some of which may be detrimental to forest health (Sherry and Holmes 1995, Williams 1936). Other species may increase the germination rates of fleshy-fruited plants through the physical removal of the skin and pulp surrounding their seeds (Greenberg and others 2001) and by gastrointestinal scarification during digestion (Traveset and others 2001). Many forest plants rely on songbirds to perform necessary seed dispersal functions and, in the case of hummingbirds, to act as pollinators. Woodpeckers, nuthatches, and other bark-foraging and excavating birds can actively contribute to the decomposition of standing dead trees and down woody debris. Forest birds can also serve as indicators of ecosystem health as some species decline or become absent when the amount, continuity, composition, and health of their habitats are changed.

A thorough understanding of the breeding habitat of a bird species or community can be very useful. The pressures of obtaining a mate and raising young, compounded by intense resource competition, greatly increases the physiological stress on birds during the breeding season (Robinson 1992). Maintaining suitable habitat for birds in their breeding range is important not only for the sustenance of the breeding adults, but these habitats also hold the potential to produce a positive input of individuals that can sustain or augment populations. Sound management and silvicultural practices on forested breeding grounds that provide for timber production while maintaining habitat integrity can be crucial to the preservation of viable populations of non-game landbirds.

Forestry practices often result in a change in density of the dominant canopy trees in the managed stand. The overstory density of a stand (i.e. the basal area of the dominant and co-dominant trees in the upper levels of a forest) is inextricably linked to canopy cover. Canopy cover, in turn, dictates the amount of light penetrating to the midstory, shrub, and ground cover layers of the forest thus affecting the entire structure and productivity of its vegetation. This affects foraging and nesting opportunities for birds as well as their exposure to predators, brood parasites, and weather. As the overstory is arguably the most ecologically important component of a forest and the most commonly altered in forest management, knowledge of the suitable overstory conditions for a songbird species, or suite of species, could help managers with the problem of applying stand-level treatments to maintain songbird habitat.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Relatively few studies have described the changes in songbird communities caused by intermediate levels of harvest (Thompson and others 1995). A number of past studies have described the bird populations and communities of different stages of forest development following past disturbance (e.g. Crawford and others 1981, Johnston and Odum 1956, Keller and others 2003, Odum 1950, Shugart and James 1973, Thompson and Capen 1988). However, the majority of avian research describing the direct effects of habitat alteration related to timber harvest have compared clearcut sites to untreated stands (Conner and Adkisson 1975, Thompson and Fritzell 1990, Thompson and others 1992, Welsh and Healy 1993). Conner and others (1979) explored the effects of clearcutting on winter bird populations, while Keller and Anderson (1992) and Germaine and others (1997) examined how breeding bird communities in small patch or strip clearcuts differed from those in uncut forests. We explored the relationship between songbird community structure and a gradient of stand manipulation associated with shelterwood regeneration. It was hypothesized that bird community composition and structure would change predictably with graded levels of forest canopy retention, as bird species select breeding territories on the treatments that best suit their habitat requirements. Here we report the preliminary results from the first post-treatment year.

METHODS

Study Area

This study was conducted in northern Jackson County, AL. Situated in the Mid-Cumberland Plateau of the southern Appalachian Mountains, this region's physiography is characterized by narrow, flat plateaus dissected with numerous deep valleys. Two sites were used, one located at Jack Gap (34° 56' 30" N, 86° 04' 00" W) and one at Miller Mountain (34° 58' 30" N, 86° 12' 30" W). The elevation range of the study sites was 260 to 520 m. Both sites were at middle to upper slope positions on the sides of the Plateau. Jack Gap had a northern slope aspect. Miller Mountain had generally southern to southwestern exposure.

Upland hardwood forest is the dominant land cover of northern Jackson County, with many large continuous tracts throughout. The forest cover of the sites and the surrounding areas was mature (80-100 years old) oak-hickory (*Quercus* spp. and *Carya* spp.) with yellow-poplar (*Liriodendron tulipifera* L.), sugar maple (*Acer saccharum* Marsh.), red maple (*Acer rubrum* L.), and American beech (*Fagus grandifolia* Ehrh.) as associates (Hartsell and Vissage 2001). These hardwood forests of North Alabama are largely owned by nonindustrial private forest (NIPF) landowners. Approximately 85 percent of the land area in forest cover belongs to this group, while commercial and public interests combined oversee 15 percent (Hartsell and Vissage 2001). Some of the largest and least fragmented tracts of mature upland forest in Jackson County are in a mixed matrix of state, industrial, and NIPF ownerships.

Design

This study consisted of three randomized complete block replicates of five overstory retention treatment units: 0 (clearcut), 25, 50, 75, and 100 percent (control). Jack Gap had two blocks and Miller Mountain had one. Each unit was roughly square in shape, and the units were arranged adjacently within each block. The treatment units were 4 ha in size making each replicate block 20 ha, and thus a total study area of 60 ha.

The clearcut, 25, and 50 percent treatments were accomplished by conventional chainsaw felling and skidding. In the 75 percent retention units, Arsenal® herbicide (active ingredient imazapyr) was applied mainly to the small diameter, midstory trees in order to reduce competition and increase light intensity for oak regeneration, without creating large overstory gaps. Application of the initial treatments was accomplished in cooperation with MeadWestvaco land managers and local logging crews in the fall of 2001 and winter of 2002. Each treatment unit had three bird survey transects spaced evenly across its width. Along each transect, marked reference points were placed at 25-m intervals to facilitate bird territory mapping. To adequately sample the entire treatment unit during spot-mapping, the distance between transects was ≤ 50 m, as was the distance from the outer transects to the parallel unit boundaries.

Overstory Measurements

Pre-treatment basal area was measured in each treatment unit at five systematically arranged 0.08-ha circular plots. Measurements within the plot from all overstory trees ≥ 14.2 cm diameter at breast height (1.4 m) were used to calculate initial basal area. Following treatment, diameter measurements of the remaining trees were used to determine residual basal area and the percentage of overstory retention. The same five plots within each treatment unit were used to measure the percentage of canopy cover following overstory removal. Five readings of a spherical densitometer were taken at breast height; one at plot center and one taken 3.6 m from plot center in each of the cardinal directions.

Songbird Community Survey

To determine the species composition, overall territory density, species richness, and diversity of the songbird communities at our study sites, territory spot-mapping was used based on the methods first described by Williams (1936) and outlined by the International Bird Census Committee (1970) and Ralph and others (1993). Most forest songbirds vigorously defend nesting and foraging territories during the breeding season and display territorial behavior that is often regular and observable. Recording this behavior and its position, as well as its relative position to the territorial behavior of simultaneously-occurring conspecifics is the basis of the spot-mapping procedure. We felt the use of the spot-mapping technique to estimate the number of breeding bird territories was a good fit for this study for the following reasons:

1. The manageable treatment size (4 ha) used in this study made the intensive effort involved in accurate spot-mapping feasible.
2. The treatment units had equal areas which help to eliminate area-dependent variation in the bird community.
3. All of the treatment units were roughly square in shape, and therefore had comparatively short total edge lengths,

thus reducing edge effects on the bird communities. This fact, coupled with the equal area of the treatments gave the units similar boundary lengths and relative edge areas, diminishing this confounding influence among and within treatments. Furthermore, the straight boundaries of the square units simplified the interpretation of territories straddling the edge.

4. One person conducted all aspects of the spot-mapping duties. This reduced inter-observer bias and differences in map interpretation, while at the same time increasing the familiarity and recent knowledge of bird activity on the treatments.

Each of the 15 treatment units received 10 spot-mapping visits between mid-April and July 2002. Ralph and others (1993) suggested this amount of sampling effort is sufficient to obtain the data necessary for the interpretation of mapped territories in forested habitats. One block of five units was visited each morning. Morning mapping surveys began between 05:00 and 05:30 depending on light conditions that varied with sunrise time and cloud cover. All surveys were completed by approximately 10:30. Within each block, the treatment unit visits were ordered systematically ensuring that every unit received equal sampling at all times of the morning survey period. Each treatment unit of the block received 1 hour of surveying per visit. This gave every unit one 10-hour spot-mapping sample over the course of the breeding season in which to develop the certainty of territory occupation. While traveling along the transects of a unit during a spot-mapping visit, the species and position of singing males were recorded on a topographic map (scale 1:1400). Nest locations and behaviors (intraspecific aggression, pair feeding, copulations, nest-building, distraction displays, food-carrying, etc.) by either sex that suggested an active territory were also noted. Data recorded on the visit maps were transferred to separate species maps for each unit. The collection of registrations for the 10 visits of a unit on each species map was used to delineate territorial activity centers. Territory density per 4 ha was assigned for each species based on the number of interpreted territorial clusters in each treatment unit.

Statistical Analysis

Univariate ANOVA was used to elucidate treatment effect among the means of all measurements. These measurements included the values for pre- and post-treatment basal area and residual canopy cover as well as the songbird community indices of territory density, species richness, and Shannon diversity index. The means for the songbird community indices and basal area data were separated using the Tukey test. The Least Significant Difference (LSD) test was used to compare the means of canopy cover in order to provide the statistical power to associate the differences in canopy cover with those of basal area retention. This is an important relationship to establish if these treatments are to be used together as a guide for songbird habitat management. Trend analysis was used to determine the functional relationship between the gradient of overstory retention and the bird community indices. Analysis was performed using SPSS version 10.0 (SPSS Inc. 1999). Significant results are reported at the $p < 0.05$ level.

RESULTS

Overstory Conditions

As expected, post-treatment basal area was different among treatments ($F_{4,8} = 42.54$, $p < 0.001$). The control and 75 percent treatments had significantly higher residual basal than the other treatments (table 1). The basal area in the clearcut units was significantly lower than that in the 50 percent plots, while the 25 percent treatment was intermediate between the two. The percentage of basal area retention showed that the applied treatments closely approximated our desired retention levels, with the largest departure from the target in the 50 percent treatments.

Three significantly different levels of canopy cover ($F_{4,8} = 19.52$, $p < 0.001$) were evident in our stands following treatment (table 1). As expected, the gradient displayed by residual basal area in our overstory retention treatments was closely reflected in the pattern of canopy cover. This gradient progressed from low values in the clearcuts for both measurements, to intermediate in the 25 and 50 percent treatments, until high values were retained in the

Table 1—Means of basal area for pre- and post-treatment conditions and percentage of basal area and canopy cover retained by treatment

	Basal area		Canopy cover	
Overstory treatment	Pre-treatment	Post-treatment	Retained	Retained
(*percent retained*)	- - - - - *m² per ha* - - - - -		- - - - - *percent* - - - - -	
0 (clearcut)	24.68a[a]	1.15a	4.7	32a
25	22.21a	6.14ab	27.6	76b
50	23.92a	9.05b	37.8	75b
75 (herbicide)	26.39a	18.47c	70.0	98c
100 (control)	23.90a	23.83c	99.7	100c

[a] Means in the same column followed by the same letter are not different at the $p < 0.05$ level.

75 percent and control treatments. The desired results in the 75 percent treatments were achieved by reducing an average of 30 percent of the midstory while effectively maintaining near complete canopy cover.

Songbird Community

Overall, 60 bird species were detected within the study area. Of these, 43 were present in the immediate area of the study sites during the breeding season, 12 species were strictly stopover migrants, and 5 were winter residents recorded in the early visits of the survey season. Thirty-four of the 43 breeding species held territories on our study sites and were used to determine species richness, total territory density, and diversity. Fourteen were permanent residents, 18 were long-distance (Neotropical) migrants, and 2 were short-distance (temperate) migrants. The seven most abundant species held 54 percent of the territories encountered (table 2). The most common breeding species was the red-eyed vireo which was the most abundant bird on the 100 percent (control) and 75 percent (herbicide) treatments. Indigo bunting was the second most common songbird and the most abundant species on the 50, 25, and 0 percent (clearcut) treatments.

Territory density—The overall territory density including all species of forest songbirds was significantly lower ($F_{4,8}$ = 9.40, $p < 0.005$) in clearcut plots than in the other four overstory treatments (fig. 1). No interaction was detected between block and treatment effects. Trend analysis showed that total territory density had a quadratic relationship ($p < 0.002$) with respect to overstory retention and a maximum density at the 50 percent level. Average density

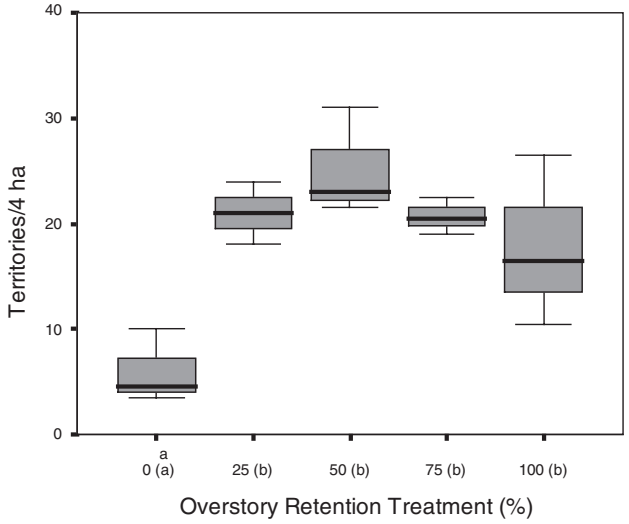

Figure 1—Average breeding bird territory density of five overstory retention treatments, different letters next to the column labels on the x-axis indicates significant difference among treatments.

was at least three times higher in the control and partial retention treatments than in the clearcut plots.

Species richness—Species richness of territorial breeding birds (fig. 2) showed a pattern similar to territory density. Control, 75, 50, and 25 percent retention treatments had similar numbers of species while the clearcuts had lower mean richness ($F_{4,8}$ = 10.39, $p < 0.005$). There was no interaction between block and treatment effects. Trend

Table 2—Territory abundance and density of seven species of songbirds accounting for 54 percent of mapped territories in five overstory retention treatments in northeastern Alabama

Species		Treatment				
		100	75	50	25	0
	n	- - - - - - - - - - -		*percent*	- - - - - - - - - - -	
Vireo olivaceus L.	33[a]	3.3[b]	3.3	2.5	1.8	—
Red-eyed vireo		(1)[c]	(1)	(2)	(3)	
Passerina cyanea L.	26.5	—	1.0	3.0	2.8	2.0
Indigo bunting			(5)	(1)	(1)	(1)
Baeolophus bicolor L.	20.5	2.0	1.7	1.8	1.2	0.2
Tufted titmouse		(2)	(2)	(4)	(6)	(7)
Thryothorus ludovicianus Lath.	18	0.8	0.7	2.2	1.3	1.0
Carolina wren		(5)	(6)	(3)	(5)	(2)
Piranga rubra L.	17	0.5	1.2	1.5	1.7	0.8
Summer tanager		(7)	(4)	(6)	(4)	(3)
Piranga olivacea Gmel.	16	1.5	1.7	1.7	0.5	—
Scarlet tanager		(3)	(2)	(5)	(9)	
Contopus virens L.	15.5	0.3	0.7	1.7	2.0	0.5
Eastern wood-pewee		(8)	(6)	(5)	(2)	(5)

[a] Total territories of species.

[b] Mean territories per 4 ha.

[c] Rank of importance within community by treatment.

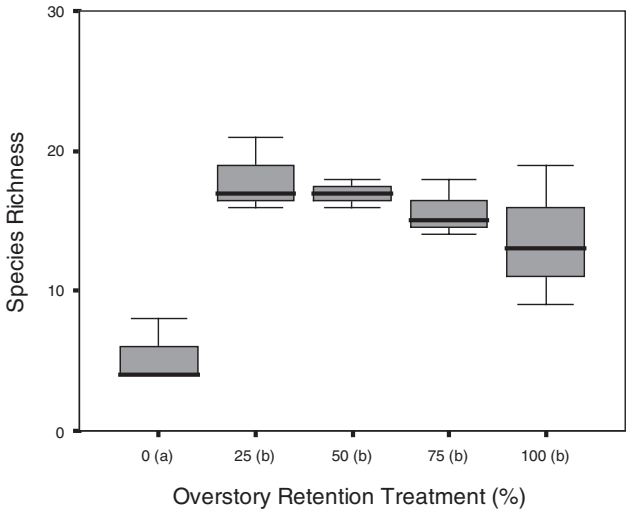

Figure 2—Means of species richness of five overstory retention treatments, different letters next to the column labels on the x-axis indicates significant difference among treatments.

analysis also revealed a quadratic relationship ($p < 0.002$) between species richness and overstory treatment. Maximum species richness was observed in the 25 percent treatments. In the control, 75, 50, and 25 percent treatments, mean species richness was at least twice that of the clearcut units.

Shannon diversity index—The Shannon diversity index was calculated for breeding songbirds holding territories on our treatments using a logarithm with base 10. Shannon diversity is a descriptive index, which in this case, takes into account the bird abundance distributed across the species richness of a particular treatment type. Treatment effect was significant ($F_{4,8} = 12.93$, $p < 0.002$) with no block-treatment interaction. Reflecting the results of territory density and species richness, the Tukey test yielded one separation for the means of Shannon diversity (fig. 3).

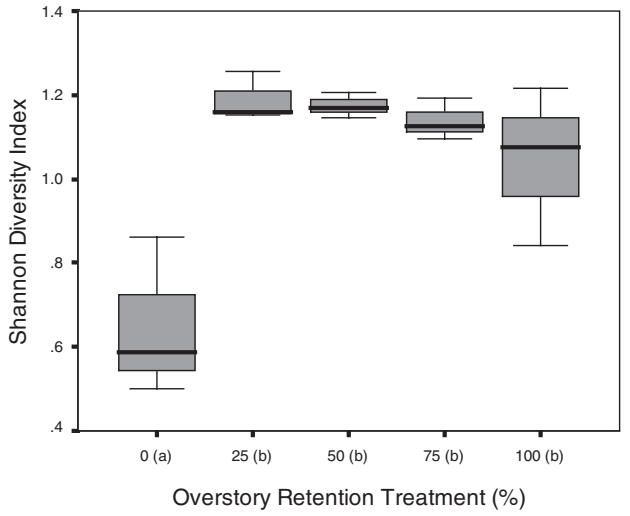

Figure 3—Means of Shannon diversity index of five overstory retention treatments, different letters next to the column labels on the x-axis indicates significant difference among treatments.

Values were lowest in the clearcut units while the other four treatments had higher diversity indices. Shannon diversity was quadratically related ($p < 0.002$) to overstory retention with a maximum mean diversity in the 25 percent treatments.

Treatment selection—Six species defended territories in just one of the retention treatments (table 3). A few species selected only one or two of the treatment types, while other generalist species held territories over a range of overstory conditions. Interestingly, 12 species that maintained territories in all but one treatment type excluded either the control or clearcut plot in their range of habitat selection. Five songbird species—Carolina wren (*Thryothorus ludovicianus* Lath.), eastern wood-pewee (*Contopus virens* L.), tufted titmouse (*Baeolophus bicolor* L.), northern cardinal (*Cardinalis cardinalis* L.), and summer tanager (*Piranga rubra* L.)—held territories in all treatment types. No single breeding bird species was unique to the clearcut treatments. Common, year-round generalists such as northern cardinal, Carolina wren, tufted titmouse, and Carolina chickadee (*Poecile carolinensis* Audu.) occurred more frequently in 25 and 50 percent treatment units.

Table 3—Breeding habitat association of 10 species with a limited range of treatment use

Species	Habitat type	
	Closed canopy forest[a]	Open canopy forest[b]
	- - - - - - - *percent* - - - - - - -	
Wilsonia citrina Bodd. Hooded warbler	X[c]	
Hylocichla mustelina Gmel. Wood thrush	X[c]	
Empidonax virescens Viei. Acadian flycatcher	X	
Cyanocitta cristata L. Blue jay	X	
Seiurus aurocapillus L. Ovenbird	X	
Passerina caerulea L. Blue grosbeak		X[d]
Sayornis phoebe Lath. Eastern phoebe		X[d]
Zenaida macroura L. Mourning dove		X[d]
Vireo griseus Bodd. White-eyed vireo		X[d]
Oporornis formosus Wils. Kentucky warbler		X

[a] 75 and 100 percent retention.
[b] 25 and 50 percent retention.
[c] Occurred only on control treatments.
[d] Occurred only on 25 percent treatments.

DISCUSSION

Our data suggested highest bird territory density in the 50 percent overstory level while richness and diversity was highest in the 25 percent overstory retention level. Although richness, abundance, and diversity were nearly as high in the 100 percent (control) and 75 percent treatments, the species composition of these closed canopy units was quite different from that of the open canopy intermediate basal area treatments (25 and 50 percent). There was some overlap between these two habitat types, but each had their own set of unique bird species. This suggests species composition may be a function of the conditions caused by the basal area and canopy cover conditions following the treatments applied in this study.

The intermediate treatments (25 and 50 percent) had six unique species, many habitat generalists, and 16 species that occurred in either the control or clearcut plots. Three species with closed canopy preferences, the scarlet tanager (*Piranga olivacea* Gmel.), red-eyed vireo (*Vireo olivaceus* L.), and tufted titmouse persisted in the intermediate treatments but declined in abundance and importance as overstory retention decreased (table 2). These points illustrate the species overlap and turnover expected with a graded change in stand retention. Dickson and others (1995) reported that bird diversity in shelterwood and seed-tree regenerated stands can be higher as a result of the immigration of early-successional species into the stands while some late-successional species remain and utilize the residual overstory. Wood and Nichols (1995) found that two-aged stands, with residual overstory and a regenerating cohort underneath, harbored greater numbers of birds and species than clearcuts or untreated stands. Our results appear to be congruent with these studies as our intermediate retention units had the greatest community indices and have high species overlap with the alternative treatments.

This study offered an interesting look into the bird community characteristics of a clearcut in the first year following treatment. Similar to Conner and Adkisson (1975) we found that bird abundance, species richness, and diversity was the lowest in clearcuts during the first post-treatment year, likely due to limited vegetative regrowth before the beginning of the breeding season. It has been widely reported that regenerating clearcuts can support abundant and diverse bird communities. Baker and Lacki (1997) showed that songbird communities in clearcuts and high- and low-leave two-aged forests had greater diversity, species richness, and abundance than in unharvested stands. However, we found that clearcut stands had the lowest density, richness, and diversity, and control stands showed values similar to the intermediate retention treatments. Keller and others (2003) reported that values of avian density and species richness for 6 year old clearcuts in the northeast were over two times that of mature stands. Our results were quite different, but it is important to stress that we studied the bird communities of clearcuts in the breeding season directly following the dormant season harvest. It is anticipated that the vegetative structure and composition in the clearcut plots will change considerably in coming years, likely leading to greater species richness and density.

From a management perspective, the results of this research would suggest the mature closed canopy habitat retained in the control and 75 percent treatments may be necessary to maintain a few unique species (table 3); the wood thrush (*Hylocichla mustelina Gmel.)* and hooded warbler (*Wilsonia citrina Bodd.)* were absent and the ovenbird (*Seiurus aurocapillus L.) was* less abundant in the 75 percent treatments. It is important to remember that most of the midstory of the 75 percent treatment was deadened using an herbicide injection. If the preservation of a species dependent on a fully-developed and living midstory is a management priority, this should be taken into consideration. On the other hand, the standing dead trees produced in the 75 percent treatment provided increased foraging opportunities for bark foraging and excavating birds that may benefit from this type of shelterwood.

The open forest habitat of the 25 and 50 percent retention treatments harbored a number of unique species and had the highest abundance, richness, and diversity. These open forest sites could be prescribed to increase richness and diversity by supporting a mixture of closed canopy, open forest, and scrub species. The clearcut plots had very low community indices and no unique species during the first breeding season following harvest. This is expected to change as years pass and further vegetative growth occurs. Perhaps forest management practices that retain some overstory and minimize understory disturbance while allowing vegetation to regenerate beneath them may be beneficial to forest songbird communities. These could be prescribed to promote desirable timber species and at the same time maintain high community indices for forest songbirds throughout a managed forest rotation by avoiding periods of low abundance and richness as in the early stages of a clearcut.

ACKNOWLEDGMENTS

This research was supported in many capacities by the Southern Research Station of the USDA Forest Service and they are gratefully acknowledged. Thanks go to the land management personnel of MeadWestvaco Corporation, Stevenson, AL, for their invaluable expertise and assistance with the application of the treatments. The Plant and Soil Science Department of Alabama A&M University provided necessary financial and logistical support.

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THE EFFECTS OF PRESCRIBED BURNING AND THINNING ON HERPETOFAUNA AND SMALL MAMMALS IN THE UPPER PIEDMONT OF SOUTH CAROLINA: PRELIMINARY RESULTS OF THE NATIONAL FIRE AND FIRE SURROGATE STUDY

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Abstract—Due to heavy fuel loads resulting from years of fire suppression, upland pine and mixed pine hardwood forests in the Upper Piedmont of South Carolina are at risk of severe wildfire. The National Fire and Fire Surrogate Study (NFFS) was conducted on the Clemson Experimental Forest to study the effects of prescribed burning and thinning on a multitude of factors, including herpetofauna and small mammals. Drift fence/pitfall arrays, modified pitfalls, unmodified pitfalls, and hand captures were used to sample herpetofauna. We captured 1,317 reptiles and amphibians representing 40 species from September 9, 2000 to January 9, 2002. There were no significant treatment effects on abundance within five major taxa (frogs/toads, salamanders, turtles, lizards, and snakes). However, there were treatment effects on two lizard species. When comparing richness, the thin treatment had a significantly higher number of snake species than the burn treatment. Live traps, snap traps, and herpetofauna traps were used to sample small mammals. No small mammals were caught in live traps for 9,600 trap nights. Snap trap success was 0.10 percent for 27,000 trap nights. Small mammals were captured at low levels in herpetofuana traps (0.06 percent trap success) for 163,968 trap nights. Treatment effects could not be determined for small mammals due to the low number of captures. Although treatment effects were limited, prescribed burning and thinning have been found to alter herpetofauna and small mammal communities.

INTRODUCTION

Herpetofauna response to forest management practices is an important issue in current wildlife research (Bury and others 1980, deMaynadier and Hunter 1995, Gibbons 1988, Lyon and others 2000, Russell and others 1999). This interest is partly due to reported declines in amphibian and reptile populations across the United States and other countries (Gibbons and others 2000, Pechmann and Wilbur 1994, Wyman 1990). The natural history and physiology of herpetofauna makes them valuable research subjects alone or in conjunction with avifauna, mammals, plants, and arthropods. Some amphibians are completely aquatic obligates while others use aquatic and terrestrial habitat in their life cycles. Consequently, forest management activities in terrestrial areas may affect the amphibian component (Bennett and others 1980). Amphibian's permeable skin is sensitive to acid rain, herbicides, pesticides, and other pollutants. This sensitivity, their use of aquatic and terrestrial environments, short life spans, and small home ranges makes amphibians good indicators of environmental quality (Pechmann and Wilbur 1994).

More than 130 species of reptiles and amphibians have been documented in South Carolina (Conant and Collins 1998, Martof and others 1980). High species density (Kiester 1971) coupled with extensive forest management in a variety of habitats (Sharitz and others 1992) makes South Carolina ideal for the study of herpetofauna response to forest management. This issue has been studied in the Coastal Plain and Appalachian Mountains but is lacking in the South Carolina Piedmont.

Southeastern forests with historically short interval, low- to moderate- severity fire regimes, have become denser and the quantity of forest fuels has increased greatly. Fuel accumulation is mostly due to successful fire suppression efforts, which degraded ecosystem integrity and increased the risk of large-scale wildfires. Each year, South Carolina suppresses nearly 4,500 wildfires. Most of these fires (80 percent) are caused by negligent debris burning or by arson. Since 1970, an average of one catastrophic wildfire of 1,000 acres or more has occurred each year in South Carolina. This average increases during droughty years. In 1985, there were 10 wildfires that averaged over 2,000 acres in size.

The NFFS was initiated on the Clemson Experimental Forest (CEF) in spring 2000 to study the ecological and economic consequences of four fuel reduction treatments over a 5 year period. The NFFS is a national study, taking place on 13 replicated study sites in the United States. It has been proposed that fuel reduction treatments, such as prescribed fire, and fire surrogates, such as cutting and mechanical fuel treatments, could restore historical ecosystem processes and increase forest sustainability. The objective of the NFFS is to use prescribed fire and thinning to understand how fuel reduction treatments affect vegetation, fuel and fire behavior, soils, wildlife, entomology, pathology, and treatment cost and utilization economics. The goal of this paper was to assess the effects of prescribed fire and thinning for fuel reduction on herpetofauna and small mammals in the Upper Piedmont of South Carolina.

METHODS

Twelve treatment areas were established in the CEF during spring 2000 based on stand age, size, tree composition, and wildfire vulnerability. Treatment areas ranged in age

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

from 15 to 60 years and were blocked by tree size to reduce variability. Each of three blocks contains four treatment areas composed primarily of pulpwood sized trees diameter at breast height (d.b.h.) (15 to 25 cm), sawtimber sized trees (d.b.h. > 25 cm), and a mixture of pulpwood and sawtimber sized trees.

Minimum block size was 14 ha to accommodate the 10-ha study plot and a buffer area of about 20 m. Tree composition was primarily planted loblolly pine (*Pinus taeda* L.) with some shortleaf pine (*Pinus echinata* Mill.), Virginia pine (*Pinus virginiana* Mill.), and various hardwood species. The last thinning occurred at least 10 years ago, and the last prescribed or wild fire occurred at least 5 years ago.

Treatments

The four treatments were randomly assigned to each block using a random number table. Treatments included thinning, prescribed burning, and an untreated control. The prescribed burn for the thin/burn treatment was not applied until data collection for this study was completed; therefore thin/burn treatments are designated as T2 in this study to distinguish them from the thin only treatment (T1). Thinning and burning levels were prescribed that reduced fuels and followed standard silvicultural practices for managed stands in the Piedmont. Thinning operations were conducted in the winter of 2000 and 2001 and prescribed burning was conducted in the spring of 2001 and 2002.

Trapping Methods

Herpetofauna was sampled using 24 drift fence/pitfall trap arrays, 120 modified pitfall traps, 120 unmodified pitfall traps, and area-constrained searches. Pitfall traps were buried 19 L plastic buckets. Two drift fence/pitfall arrays (Crosswhite and others 1999) constructed of nylon silt fencing were randomly located in the upper and lower half of the treatment area. Drift fence/pitfall arrays were Y-shaped with 10-m arms spaced 120° from each other. Each array had four pitfalls, one pitfall in the center and one at each arm end. Modified pitfalls were placed every 200 m and alternated with unmodified pitfalls. Pitfalls were modified by burying three 1-m sections of aluminum flashing at 120° angles to the pitfall opening. Any herpetofauna captured by hand or heard vocalizing within the treatment areas were counted as hand captures.

Marking Techniques

All herpetofauna captured were identified to species, marked, sexed, weighed, and measured. Taxonomy followed that of Conant and Collins (1998), Highton and Peabody (2000), and Martof and others (1980). Frogs/toads, salamanders, and lizards were marked by toe clipping the fourth outermost toe on the right rear foot with a pair of small scissors (Donnelly 1989). Snakes were marked by scale clipping the end of the fifth ventral plate. Turtles were marked by marginal scute filing. Scale clipping and scute notching methods were modifications of those used by Woodbury (1953).

Statistical Analysis

Herpetofauna data were summarized for all captures from September 9, 2000 to January 9, 2002 and for post-treatment captures from April 11, 2001 to January 9, 2002. Captures were totaled for each species within five major taxa for each sampling period, trap type, and month. Only captures from April 11, 2002 to January 9, 2002 were used to test for treatment effects. Tests for treatment effects on abundance and richness were conducted on treatment and major taxa totals and for 11 individual species with the highest abundance: green anole (*Anolis carolinensis* Voigt), Fowler's toad (*Bufo fowleri* Hinckley), eastern worm snake (*Carphophis a. amoenus* Say), five-lined skink (*Eumeces fasciatus* L.), eastern narrowmouth toad (*Gastrophryne carolinensis* Holbrook), southern appalachian salamander (*Plethodon teyahalee* Hairston), bullfrog (*Rana catesbieana* Shaw), ground skink (*Scincella lateralis* Say), northern fence lizard (*Sceloporus undulatus hyacinthinus* Green), southeastern crowned snake (*Tantilla coronata* Baird and Girard), and eastern box turtle (*Terrepene c. carolina* L.). Captures from September 9, 2000 to January 9, 2002 were used for trap efficiency analysis.

The General Linear Model (GLM) procedure and Least Significant Difference (LSD) tests in SAS (1999) were used to test for treatment effects and differences in trap efficiency. The level of significance was set at $\alpha = 0.05$ for all statistical tests.

RESULTS AND DISCUSSION

Herpetofauna

During the overall sampling period, we captured 1,317 reptiles and amphibians representing 40 species in 163,968 trap nights. Lizards (49.1 percent) were the most abundant taxon followed by frogs/toads (23.5 percent), snakes (13.7 percent), salamanders (9.2 percent), and turtles (4.6 percent). The majority of captures, 52.8 percent reptiles and 28.6 percent amphibians, occurred from April 2001 to October 2001. Total post-treatment sampling produced 1,146 captures representing 40 species for 92,064 trap nights. Lizards (47.7 percent) were the dominant taxon followed by frogs/toads (25.7 percent), snakes (14.2 percent), salamanders (7.9 percent), and turtles (4.5 percent).

S. u. hyacinthinus was the most abundant species overall and in post-treatment sampling, representing 25.5 percent and 24.3 percent of total captures, respectively. *B. fowleri*, *A. carolinensis*, *E. fasciatus*, and *T. coronata* were the next four dominant species forming a group representing 34 percent of total captures overall and 36 percent in the post-treatment sampling period. No significant treatment effects on abundance were found for the five major taxa (table 1). Although post-treatment sampling occurred throughout the peak months of activity (April to October) more sampling is needed during this time over successive years to detect treatment effects.

When comparing richness, T1 had significantly higher number of snake species than the burn treatment (table 2). However, 50 percent of snake richness was made up of species represented by only one capture per plot. The difference in snake richness pertained more to random encounter with a trap rather than the effects of the burn. There were no significant treatment effects when comparing the total treatment abundance and richness. Of the

Table 1—Mean herpetofauna abundance (captures/treatment) for post-treatment sampling

Treatment	Frogs and toads	Salamanders	Turtles	Lizards	Snakes	Overall
Burn[a]	12.6 a[b]	3.0 a	3.6 a	39.7 a	9.6 a	13.7 a
Control	37.3 a	8.3 a	4.3 a	27.7 a	14.3 a	18.4 a
T1	26.0 a	7.0 a	4.0 a	54.7 a	18.0 a	21.9 a
T2	22.0 a	12.0 a	5.0 a	60.3 a	12.3 a	22.3 a

T1 = thin only treatment; T2 = thin/burn treatment.
[a] Burn only treatment.
[b] Means not followed by the same letter within columns differ significantly at $p < 0.05$.

Table 2—Mean herpetofauna richness (number of species and treatment) for post-treatment sampling

Treatment	Frogs and toads	Salamanders	Turtles	Lizards	Snakes	Overall
Burn	2.7 a[a]	2.0 a	1.3 a	4.6 a	3.0 a	2.7 a
Control	5.7 a	2.0 a	1.0 a	5.0 a	4.7 ab	3.7 a
T1	4.0 a	3.7 a	1.0 a	5.0 a	5.0 a	3.9 a
T2	4.3 a	4.0 a	1.0 a	5.3 a	5.3 ab	4.0 a

T1 = thin only treatment; T2 = thin/burn treatment.
[a] Means not followed by the same letter within columns differ significantly at $p < 0.05$.

11 individual species chosen for analysis, there were significant treatment effects on *A. carolinensis* and *E. fasciatus* (table 3). T2 had significantly more *A. carolinensis* captures than the burn or control. There were significantly more *E. fasciatus* captures in the T2 and T1 than in the control. *A. carolinensis* and *E. fasciatus* activity increased due to the conditions created by overstory removal. Thinning reduced basal area within the treatment area (Phillips and others, in press). Thinning increased the amount of sunlight reaching the forest floor resulting in a higher proportion of area available for thermoregulation.

Much of the amphibian abundance and richness in this study can be explained by the presence of adjacent breeding habitat. Amphibians made up 33.6 percent of post-treatment captures and were primarily composed of species uncharacteristic of upland pine plantations. This could be due to the presence of adjacent breeding habitat to the treatment areas. Beaver ponds, perennial streams, and intermittent streams are in close proximity to treatment areas. Different habitat among blocks may have produced enough variability to mask significant differences among treatments.

Table 3—Average abundance of individual species by treatment

Species	Burn	Control	T1	T2
Anolis carolinensis	5.0 a[a]	2.0 a	7.3 ab	17.7 b
Bufo fowleri	9.0 a	2.7 a	20.3 a	12.7 a
Carphophis a. amoenus	1.3 a	4.7 a	3.3 a	4.4 a
Eumeces fasciatus	7.0 ab	4.3 a	11.7 b	9.6 b
Gastrophyrne carolinensis	2.0 a	3.0 a	3.0 a	4.7 a
Plethodon teyahalee	1.7 a	8.7 a	1.7 a	5.7 a
Rana catesbieana	1.3 a	9.0 a	5.2 a	2.3 a
Scincella lateralis	5.2 a	3.3 a	4.6 a	3.0 a
Sceloporus undulatus hyacinthinus	22.7 a	14.7 a	27.7 a	28.0 a
Tantilla coronata	7.0 a	5.7 a	9.3 a	4.3 a
Terrapene c. carolina	3.3 a	4.3 a	4.0 a	5.0 a

T1 = thin only treatment; T2 = thin/burn treatment.
[a] Means not followed by the same letter within columns differ significantly at $p < 0.05$.

Trap Efficiency

Drift fence/pitfall arrays accounted for 32.3 percent of total captures while modified pitfalls accounted for 30.4 percent. Unmodified pitfalls and hand captures made up 19.2 and 18.0 percent of total captures, respectively. Both drift fence/pitfall arrays and modified pitfalls caught 30 species. Twenty-five species were caught in unmodified pitfalls and 19 species were caught by hand.

There were no significant differences in capture efficiency among trap types for frogs/toads, salamanders, or lizards or for overall capture abundance (table 4). Significantly higher numbers of *T. c. carolina* were caught by hand than by array, modified pitfall, and unmodified pitfall. Modified pitfalls caught significantly more *T. c. carolina* than unmodified pitfalls. Arrays caught significantly higher numbers of snakes than modified pitfalls, unmodified pitfalls, and hand capture.

Array efficiency for snakes, especially *T. coronata*, supported the findings of other trap efficiency studies. Preferred prey for this species are centipedes and insect larvae (Conant and Collins 1998, Martof and others 1980). Arrays may capture more of the preferred *T. coronata* prey than the other trap designs. Abundant species such as *S. u. hyacinthinus* were caught in all trap types with the same relative efficiency. This may be due to the diurnal nature of this species and the amount of area it covers during active periods. During peak breeding activity in the spring, male *S. u. hyacinthinus* are actively seeking females and cover more area. Evidence of this increased activity was reflected by the increase in multiple male captures per pitfall. There were several instances where four or five different males were caught in a single pitfall during the spring. For most of the study, one capture per pitfall was usual.

There were no significant differences in capture efficiency for richness among trap types for frogs/toads, salamanders, and turtles (table 5). Unmodified pitfalls caught significantly more lizard species than hand capture. Significantly more snake species were caught in the array and modified pitfalls than by unmodified pitfalls and hand capture. Overall, there were significantly fewer species caught by hand and unmodified pitfalls than by the other two trap types.

Richness analysis found that trap efficiency varied for lizards, snakes, and the overall number of species captured. Unmodified pitfalls were more efficient for lizards than hand capture because this trap type consistently caught more species of *Eumeces* (Wiegmann). *A. carolinensis*, *S. u. hyacinthinus*, and *S. lateralis* were species common to both hand and unmodifed pitfall traps. However, unmodified pitfalls were more efficient at catching *Eumeces* than hand capture. For each replication, unmodified pitfalls consistently caught two or three species of *Eumeces*, but no more than one of three species was ever caught by hand. *Eumeces* are alert and very active lizards (Contant and Collins 1998) and are much more difficult to capture by hand than *A. carolinensis*, *S. u. hyacinthinus*, and *S. lateralis*.

Table 4—Capture abundance for array, hand, modified, and unmodified trap types

Treatment	Frogs and toads	Salamanders	Turtles	Lizards	Snakes	Overall
Array	34.3 a[a]	20.0 a	3.8 a	53.0 a	32.3 b	30.5 a
Hand	18.7 a	—	13.0 b	42.3 a	5.0 a	19.8 a
Modified	35.0 a	14.0 a	3.7 a	68.0 a	13.0 a	26.7 a
Unmodified	15.0 a	9.5 a	1.3 a	52.0 a	9.7 a	17.8 a

— = Taxon was not present.

[a] Means not followed by the same letter within columns differ significantly at $p < 0.05$.

Table 5—Species richness for array, hand, modified, and unmodified trap types

Treatment	Frogs and toads	Salamanders	Turtles	Lizards	Snakes	Overall
Array	5.3 a[a]	4.0 a	1.5 a	5.3 ab	6.0 a	4.6 a
Hand	3.7 a	—	1.0 a	4.0 a	3.3 b	3.0 b
Modified	5.0 a	5.3 a	1.0 a	5.3 ab	4.0 a	4.1 a
Unmodified	3.7 a	3.2 a	1.0 a	5.7 bc	3.3 b	3.4 b

— = Taxon was not present.

[a] Means not followed by the same letter within columns differ significantly at $p < 0.05$.

CONCLUSIONS

Prescribed burning and thinning for fuel reduction had minimal effects on herpetofauna in upland pine plantations of the Piedmont. Opening the forest canopy by thinning (Phillips and others 2004) created favorable conditions for two lizard species (*A. carolinensis* and *E. fasciatus*). Adjacent breeding habitat appears to have influenced the abundance and richness of amphibians in a treatment area more than did prescribed fire and thinning. These findings are based on intensive sampling of herpetofauna with a variety of methods and knowledge of land use adjacent to treatment areas. Because prescribed burning and timber harvest have been documented as having definite effects on herpetofauna, further post-treatment research should be conducted to expand on the baseline data collected thus far.

ACKNOWLEDGMENTS

The authors thank Peter R. Kapeluck, Ross J. Phillips, and Victor B. Shelburne for their insightful comments on the manuscript. Zack Featherstone, Anna P. Kilpatrick, Shaun C. Worley, and Luara A. Zebehazy assisted in field work, and James Williams assisted in data analyses. This is contribution Number 27 of the National Fire and Fire Surrogate Project (NFFS), funded by the U.S. Joint Fire Science Program.

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Fire Ecology

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LITTER DECOMPOSITION AND SOIL RESPIRATION RESPONSES TO FUEL-REDUCTION TREATMENTS IN PIEDMONT LOBLOLLY PINE FORESTS

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Abstract—As part of the National Fire and Fire Surrogate Study, we measured the short-term effects of different fuel-management practices on leaf litter decomposition and soil respiration in loblolly pine stands on the upper Piedmont of South Carolina. These stands had been subjected to a factorial arrangement of experimental fuel-management treatments that included prescribed burning, selective thinning, and a combination of thinning and burning. First-year results indicated that decomposition of leaf litter was significantly slower in thinned stands than in burned or control stands, and that nitrogen dynamics were variable over time in thinned and burned stands relative to controls. Soil respiration was lower in burned stands than in control or thinned stands, possibly due to fire-induced reductions in potentially mineralizable carbon pools in the forest floor. These results suggest that carbon and nitrogen dynamics are significantly altered by thinning and burning, but these alterations are manifested in fundamentally different ways.

INTRODUCTION

The need for a comprehensive strategy for managing forest fuels to minimize the risk of wildfires on Federal, State, and private lands is increasingly apparent. This is true for forested systems across North America, including forests in the Southeast that were historically regulated by frequent low-intensity fires, but where long-term fire suppression has resulted in unprecedented fuel accumulations. Prescribed fire and selective thinning are practices commonly used to manage fuel loads in forests with heavy fuel loads. Although these fuel-load management practices may be effective for mitigating wildfire risk, comparatively little is known about how these treatments may affect other components of system function. In addition to reducing fuel loads, these practices are likely to affect numerous other ecosystem characteristics, including pool sizes and flux rates of carbon (C), nitrogen (N), and other nutrients.

Net storage or loss of C in ecosystems is of critical interest to land managers, as atmospheric concentrations of CO_2 continue to rise far beyond levels observed in recent earth history (Schlesinger 1997), raising concerns about how these CO_2 concentrations may detrimentally influence global climate patterns. Some proposals for mitigation of future CO_2 production rely on rewarding the long-term fixation and storage of C in biological or other pools with "carbon credits." Thus, information about how landscape-scale applications of thinning or prescribed fire influence C dynamics should be of interest to land managers, environmentalists, industrialists, and politicians alike. Current estimates suggest that about 10 percent of the total C pool in the atmosphere is fixed by vegetation, cycled through soil, and passed back into the atmosphere as soil respiration every year (Schlesinger and Andrews 2000). Landscape-scale changes in land use or land management; e.g., increased use of prescribed fire or thinning, have the potential to alter regional patterns of fixation or respiration, and thus could result in either increased net storage of C in terrestrial sinks or net losses of C to atmospheric pools.

Fire effects on soil fertility have been studied extensively for Coastal Plain forests, but much of this work has focused on total soil organic matter and not necessarily on fluxes of C or N (e.g., McKee 1991, Moehring and others 1966, Wells 1971). Exceptions include the work of Schoch and Binkley (1986) and Bell and Binkley (1989), which examined studies of N dynamics in postfire soils on the South Carolina Coastal Plain. Management effects on pools and fluxes of C and N in fire-prone systems have begun to be studied in western forests of the United States (e.g., Baird and others 1999, Choromanska and DeLuca 2002, Kaye and Hart 1998), but this type of study has been rare in southeastern Piedmont pine forests. Objectives for this study were to determine short-term effects of prescribed fire, selective thinning, and a combination of thinning and burning on C and N fluxes in decomposing leaf litter, and C flux as soil respiration in pine forests of the Piedmont.

MATERIALS AND METHODS

Site Description

We conducted this study on the Clemson Experimental Forest located on the upper Piedmont of South Carolina (82°50′W., 34°40′N.). Climate at the site is mild, with average temperatures of 25.5 °C in July and 5 °C in January, and average annual precipitation of 121 cm. Vegetation at the site is dominated by southern pines with loblolly (*Pinus taeda* L.), shortleaf (*P. echinata* Mill.), and Virginia pine (*P. virginiana* Mill.) all well represented in the overstory. Understory vegetation is mixed hardwood with red maple (*Acer rubrum* L.), flowering dogwood (*Cornus florida* L.), blackgum (*Nyssa sylvatica* Marsh.), and various oaks (*Quercus* spp.) making up the majority of trees, and blueberry (*Vaccinium* spp.) as the dominant understory

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

shrub. There are also numerous species of herbs, grasses, and vines present in these forests. Soils on the Clemson Experimental Forest are generally classified as Typic kanhapludults or Typic hapludults, with the majority falling into Pacolet, Madison, Cecil, and Tallapoosa soil series.

Experimental Design

Experimental units used in this study were arranged in a completely randomized block design with three replicate plots in each of three treatments. Treatments included prescribed fire, selective thinning, a combination of thinning and burning, and an untreated control. Fire treatments were applied as stripped head fires in April and May of 2001, and all thinning was conducted by feller buncher to basal area of 80 square feet per acre in the winter of 2000–01. For the thinning-plus-burning combination treatment, fires were applied in April of 2002 on plots where slash from the thinning was burned along with accumulated fuels. All treatments were blocked by stand age: the first block was pulpwood-aged timber (15 to 20 years), the second block was a mixture of pulpwood and sawtimber (20 to 30 years), and the third block was predominantly sawtimber-aged (30+ years). Each experimental replicate was approximately 6 to 10 ha in area, and at least 36 permanent sampling points were established on a grid at 50-m intervals.

Leaf Litter Decomposition

Litter bags were used to determine rates of litter decomposition in each of the fuel treatments examined in the experiment. Pine litter was collected on tarps suspended over ground level in a stand of loblolly pine that had been attacked by southern pine beetle. This allowed us to collect uniform-quality senesced pine litter in large quantities before it came into contact with the forest floor. Approximately 5 g of this litter was placed inside a bag made of fiberglass window-screen mesh (aperture approximately 0.2 mm), and in November 2000, 12 of these bags were placed on the forest floor at 5 grid points within each experimental replicate. Because fire had not yet been applied to the thin-plus-burn plots, only three treatments were used for this part of the study (thin, burn, and control). One bag was collected from each grid point every 2 months (for a total of 5 bags from each treatment unit or 45 bags per sample date). Contents were removed, dried at 55 °C for at least 48 hours, and weighed to determine mass lost due to decomposition. Carbon and N concentrations for initial litter material and bimonthly litter bag samples were determined by micro-Dumas combustion on a Perkin-Elmer 2400 Series II CHNS/O analyzer.

Soil Respiration

We measured soil respiration at five locations within each experimental replicate, roughly corresponding (within 15 m) to the locations of the litter bags. Respiration was measured using a Licor 6400 infrared gas analyzer with a soil chamber attachment. We selected one live tree, 25 to 35 cm in diameter, nearest the permanent grid point within the experimental replicate, and measured soil respiration at two distances (50 cm and 150 cm) from the base of the selected tree. We took the average of the two observations at each location, for a total of five observations for each treatment unit.

Data Analysis

Because litter bags were only deployed in three treatment types, we analyzed litter decomposition data by one-way analysis of variance (ANOVA) with burn and thin as treatment variables. Soil respiration data were analyzed by two-way ANOVA with burn and thin as main effects variables; i.e., interactions between burn and thin were also examined. Averages of observations for all variables made within the same experimental unit were used for ANOVA procedures; thus, N = 3 for each treatment for all analyses.

RESULTS AND DISCUSSION

Litter Decomposition

The most basic measure of litter decomposition, mass loss over time, revealed no significant differences in absolute mass lost between treatments in this study. However, another useful expression of mass loss is often achieved by calculating rate of decay (k) as the slope of a regression line for percent of litter mass remaining vs. time (Coleman and Crossley 1996). In our study, this calculation showed that the rate of decay for litter in thinned stands was slower (0.077 d^{-1}) than in burned or control stands (0.088 and 0.093 d^{-1}, respectively) (fig. 1). Although this difference is small, when projected on an areal basis, slower decomposition rates in thinned stands would result in larger accumulations of litter on the soil surface over time.

When individual elements were analyzed in litter from the litter bags, our data suggested that C was lost at a similar rate in all three treatments. There was no significant difference in the proportion of original litter C remaining between control stands and stands that had burned or thinned (fig. 2A).

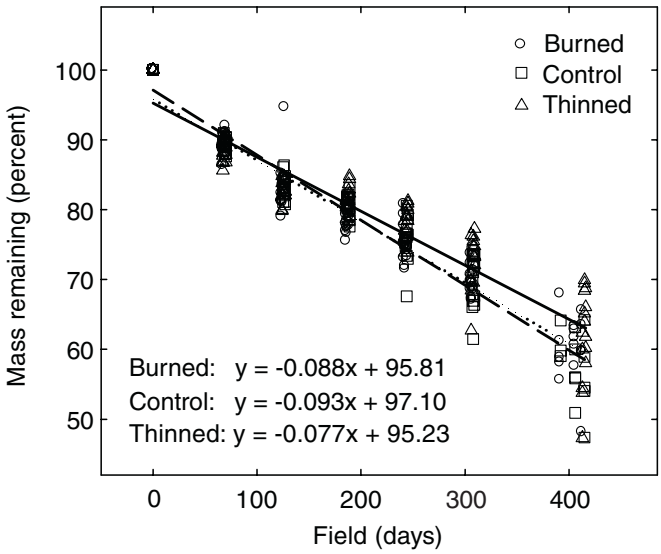

Figure 1—Linear regressions for determination of decay constants (k = percent mass loss d^{-1}) for pine litter in fire and fire surrogates study plots at Clemson Experimental Forest, SC. Each symbol represents an individual litter bag. Triangles and solid line represent bags from thinned stands; circles and dotted line represent bags from burned stands; squares and dashed line represent bags from control stands. Linear equations are shown for each treatment as $y = k(x) + b$, where y = estimated percent mass remaining, k = decay constant, x = days in the field, and b = y-intercept.

There were significant treatment effects on the dynamics of N in decomposing leaf litter. N concentrations were highly variable in material from litterbags in thinned units and burned units, whereas N concentrations were less variable over time in control units (fig. 2B). Litter from thinned and burned units had significantly lower concentrations of N on dates 3 and 5, but these differences were not observed on dates 4 and 6. The variable concentrations of N in leaf litter in the thinned and burned stands may be related to temperature and moisture conditions in the litter at the time of collection. Previous studies demonstrate that N and other nutrients can move into or out of decomposing litter as conditions become more or less favorable for decomposer organisms (e.g., Blair and Crossley 1988, Blair and others 1992). We did not directly measure litter temperature or moisture content, but thinning and burning both reduce canopy cover and remove all or part of the litter layer. Thus, temperature and moisture at the soil surface (and therefore N content of litter) are likely to be more variable in these stands than in controls.

Litter quality also influences rates of decomposition, and the ratio of C to N (C:N) in litter materials is commonly used as a measure of litter quality. In general, litter with higher C:N is considered to be of lower quality, as this material is more difficult to metabolize for decomposer organisms (Swift and others 1979). In this study, we observed significant treatment differences in C:N of decomposing litter. There was no difference in C:N for the first two sampling dates, but by the third sample date a trend of higher C:N in litter from thinned stands had emerged (fig. 2C). The difference between thinned stands and control stands was statistically significant for dates 3, 5, and 6. Additionally, on the fifth and sixth dates, we observed significantly higher C:N in litter from burned stands relative to controls (fig. 2C). Higher C:N ratios in litter from thinned stands partially explain the observed trend of slower decomposition of litter in these stands noted above (fig. 1). Given higher C:N in litter from burned stands, future sampling may reveal a slower rate of litter decomposition in these stands as well.

Soil Respiration

Soil respiration data indicated that burning significantly reduced the rate of CO_2 efflux from plots in this experiment (fig. 3). This pattern was observed in plots that were burned only, as well as in plots that were thinned and then burned. Thinning alone had no effect on CO_2 efflux relative to controls. The combustion of organic matter in forest floor litter (Oi) and duff (Oe + Oa) is possibly responsible for the reduction in respiration, as the loss of this organic matter represents a coincident loss of at least some portion of the potentially mineralizable C pool. This idea is supported by the findings of Shelburne and others (in press) that indicated a reduction in concentrations of Oa horizon soil C in burned stands relative to controls in the same study. Another explanation may be the higher soil temperatures and lower soil moisture in burned stands relative to thinned or control stands. The blackening of the soil surface that occurs with prescribed fire may result in increased absorption of solar energy as well as increased soil temperatures and soil drying. There is a well-known relationship between temperature, moisture, and soil respiration, with respiration rates decreasing at high temperature and low moisture (Singh and Gupta 1977). Decreased root respiration from trees in burned stands is another possible cause for the observed patterns of decreased respiration in burned stands. This pattern would be observed if the fire had damaged roots or aboveground tissues such that root respiration would be reduced.

Thinning; i.e., reducing canopy cover, could also result in increased solar energy reaching the forest floor, increasing temperature, but the removal of the litter layer is much less uniform with thinning than with prescribed fire. Because the litter layer provides a buffer against diurnal fluctuations in temperature and humidity, forest floor in thinned stands may

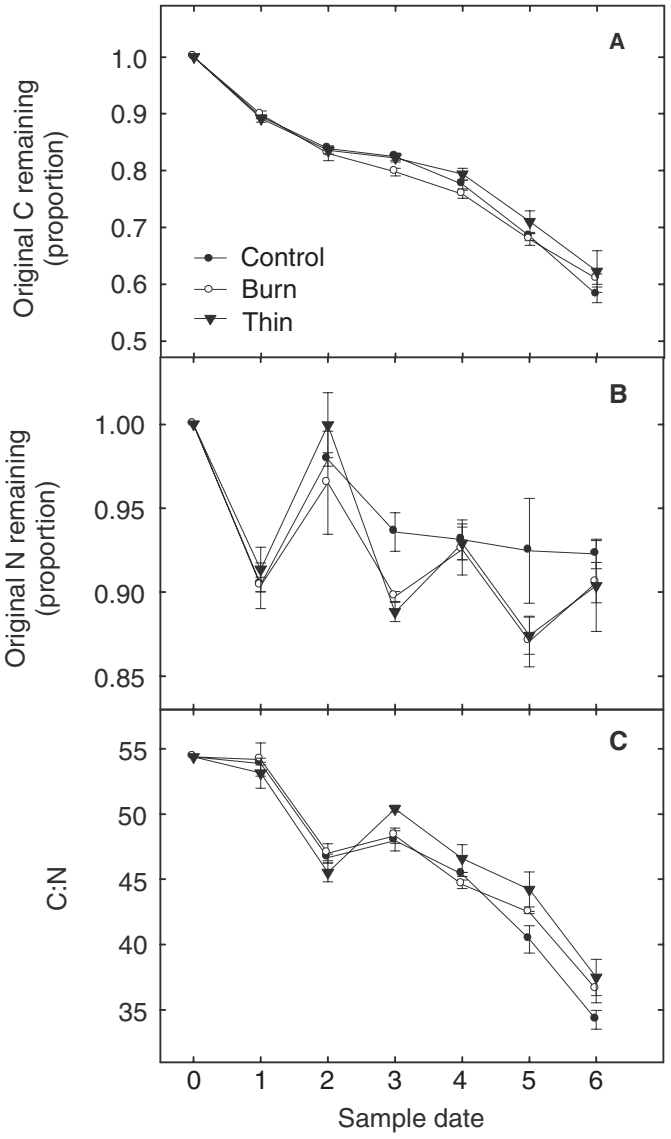

Figure 2—Leaf litter decomposition in fire and fire surrogates study plots at Clemson Experimental Forest, SC. (A) Proportion of original carbon remaining, (B) proportion of original nitrogen remaining, (C) carbon to nitrogen ratio [carbon (C), nitrogen (N)]. For all plots values are means (n = 3), and error bars indicate standard error, open circles represent bags from burned plots, closed triangles represent bags from thinned plots, and closed circles represent bags from control plots.

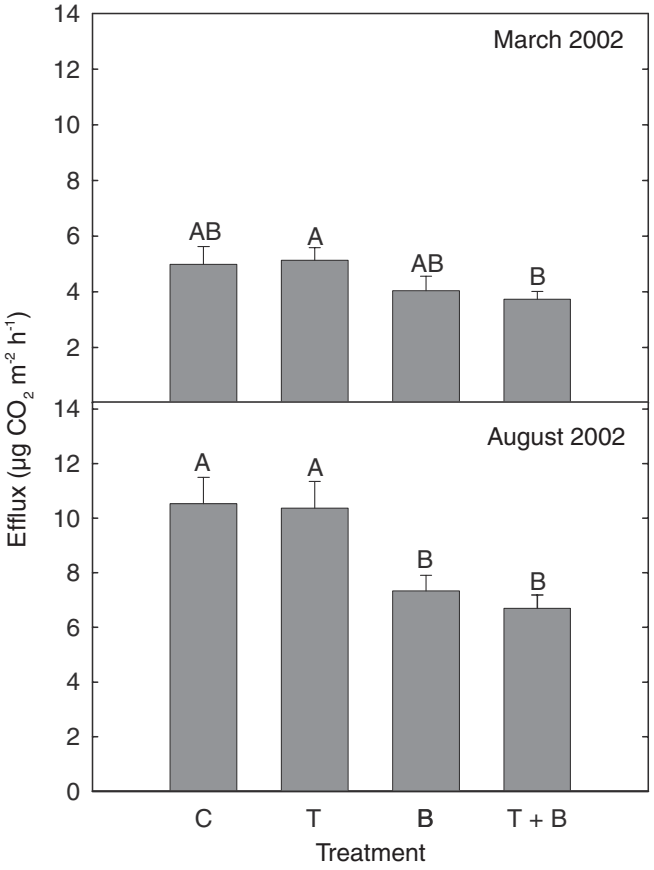

Figure 3—Soil respiration (CO_2 efflux) from fire and fire surrogates study plots at Clemson Experimental Forest, SC. Bars are means (n = 3), and error bars indicate standard error. Treatments are C = control, T = thinned, B = burned, and T + B = thinned and burned. Bars with different letters were significantly different ($p < 0.05$).

not experience much warmer or drier conditions than control stands. Thus, the difference in respiration rates between burned and thinned stands may be explained by the composition and structure of the forest floor.

CONCLUSIONS

The effects of thinning and burning on C fluxes examined in this study provide evidence that these management practices can have measurable impacts on the movement of C through this system. However, drawing conclusions about what these differences might mean with respect to net loss or storage of C for each management system is problematical. The decreased rates of litter decomposition in thinned stands observed in this study suggest that, at least in the short term, more C would be stored in the forest floor of thinned stands than in unmanaged stands. However, effects of thinning on the fixation of C are not well characterized for our study plots; thus, the net effect of thinning on C storage is not yet known. Likewise, the decreased respiration rates observed in the burned plots suggest the potential for net storage of C as less CO_2 returns to atmospheric pools from soils in burned stands. However, the amount of CO_2 produced by combustion of litter materials during the actual fire event (or reduced fixation of C by plants after fire) may offset any gains due to reduced efflux of CO_2 after the fire. The duration of the reduced respiration will be an important factor in determining the net effect of fire on C storage in these systems. Developing more complete C budgets for these management systems, including vegetation effects, combustion effects, and soil temperature effects on biological activity in soils, should improve our ability to predict cycling and storage of C and dynamics of N.

ACKNOWLEDGMENTS

This is Contribution Number 31 of the National Fire and Fire Surrogate Project, funded by the U.S. Joint Fire Science Program. The authors wish to thank Helen Mohr, Gregg Chapman, Chuck Flint, and Ross Phillips for assistance in the field, and Corey Babb for assistance in the laboratory.

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IMPACTS OF GROWING-SEASON PRESCRIBED BURNS IN THE FLORIDA PINE FLATWOODS TYPE

Kenneth W. Outcalt and John L. Foltz[1]

Abstract—A considerable amount of experience and knowledge has been gained in the application of growing-season burning in pine communities across the Southeast. However, there is still concern that burning during this season will cause increased tree mortality and/or growth loss. Pine flatwoods stands in south Florida with 3 years of fuel accumulation were burned during the growing season using rather aggressive head-firing techniques. Crown scorch ranged from a low of 16 percent to a high of 83 percent. The lowest crown scorch occurred on treatment units burned mostly with flanking fires. Although scorch was quite high in some units, mortality was not significantly increased by growing-season burns. The probability of mortality and growth loss can be minimized by using firing techniques that produce less intense burns and by avoiding burns during the late growing season or when trees are already stressed.

INTRODUCTION

The pine flatwoods were a predominate ecosystem of the Southeastern Coastal Plain (Sargent 1884) prior to European influx. They were most abundant in Florida, occupying 50 percent of the area (Stout and Marion 1993). Pine flatwoods, a cryptic term, is based on the lack of relief and the open pine-dominated tree layer composed of longleaf (*Pinus palustris* Mill.), slash (*P. elliottii* Engelm.), south Florida slash (*P. elliottii* var. *densa* Little & Dorman), and pond pine (*P. serotina* Michx.) (Abrahamson and Hartnett 1990). Saw palmetto [*Serenoa repens* (Bartr.) Small], gallberry (*Ilex glabra* L.), and grasses are typical understory dominates.

Some of the annually shed resinous needles from overstory pines become entangled in the emergent understory vegetation. Saw palmetto and the predominant shrubs have waxy leaves that will burn quite easily. Coupled with the suspended needle fall and accumulation of dead grass, this creates a very flammable condition (Landers 1991). Florida has more thunderstorm days than anywhere else in the United States, and therefore a very high incidence of lightning strikes (Chen and Gerber 1990). Historically, this combination of rapid accumulation of pyrogenic vegetation and an abundant ignition source resulted in a fire frequency of 1 to 3 years (Frost 1998). Thus, pine flatwoods vegetation has evolved with and is dependent upon frequent low-intensity fires.

Because pine flatwoods are quite productive, understory fuels accumulate quickly, which can lead to severe wildfires (Davis and Cooper 1963). Forestry organizations initially attempted to quell these wildfires by detection and rapid attack to extinguish them. This worked for a time, but as fuel levels increased it became obvious that fires could not always be stopped, especially during periodic droughts. Research and practical application began to demonstrate the usefulness of fire to control fuel buildup, thereby reducing the probability of destructive wildfires. It was also recognized that fire had beneficial effects for forestry and the ecosystem when applied under controlled conditions. Thus, we entered an era of application of prescribed burns by trained professionals to obtain desired management objectives (Wade and Lunsford 1989).

Most of these prescribed burns were done during the dormant season when weather and fuel moisture conditions were generally favorable for fuel reduction burns. It was known, however, that growing-season burns could be more effective at controlling understory shrubs and invading hardwoods (Lotti 1956). More recently, research has shown that growing-season burns not only more closely mimic natural ignitions, especially in the early part of the growing season during the normal spring drought, but they also have important ecological benefits (Robbins and Myers 1992, Streng and others 1993). Based on this information and knowledge gained through adaptive management, most natural resource agencies had begun a program of growing-season burning by 1990 (e.g., Ferguson 1998). Although practitioners have gained a considerable amount of experience in applying growing-season burns, some burns still result in considerable crown scorch and sometimes tree mortality. The overall objective of this study, part of the nationwide fire and fire surrogate study (Weatherspoon 2000) is to develop realistic management options that can be used to treat fuels and restore flatwoods ecosystems. This paper covers the effectiveness of growing-season burns for reducing fuel loads without causing unacceptable damage to overstory trees.

METHODS

Study Site

The study is located about 25 km southeast of Sarasota, FL (27°14′N., 82°19′W.) in the Myakka River State Park. The climate is subtropical, characterized by high temperatures and humidity, declining only moderately during the winter. Moisture is abundant with most rainfall arriving as convective afternoon thunderstorms during the summer or wet season. The terrain is nearly level with slopes typically

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

< 1 percent and an elevation of < 15 m above sea level. The soils, developed from unconsolidated marine sediments, are dominated by the Myakka series (Aquods). Myakka soils are wet, often poorly drained sands with an organic-stained subsoil layer occurring at a depth of 60 cm.

The park is managed by the Division of Recreation and Parks under the Florida Department of Environmental Protection. Both longleaf pine, which is near the southern limit of its range here, and south Florida slash pine stands occur in the park, with the latter dominating the southern region. These flatwoods systems are dominated by ascendant saw palmetto beneath a canopy of scattered pines, live oak (*Quercus virginiana* Mill.), and sabal palm [*Sabal palmetto* (Walt.) Lodd. ex Schultes]. The systems under management by Myakka River State Park are representative of all stages of succession possible within flatwoods. Destructive wildfires can be expected in this southern rough fuel complex found in flatwoods and Florida dry prairie when normal fire-return intervals of 3 to 5 years are exceeded. To keep fuel levels in check, park personnel have been burning much of the site on a 3-year rotation since the early 1980s.

Layout and Experimental Design

The basic design was a randomized block with three blocks and five treatment units in each. The blocks were different locations that contain a representative sample of conditions found in these flatwoods systems. Block 1 was a relatively dry site with an overstory dominated by slash pine, mostly a north Florida variety from a former plantation, with smaller amounts of natural longleaf pine. Block 2 was also a relatively dry area, but it does become wet during the peak of the late summer rainy season. It was dominated by natural longleaf pine. Block 3 was a relatively wet site that dries out during the dormant dry period but can be quite wet, with water at or above the soil surface during a good portion of the summer rainy period. South Florida slash pine dominated the overstory of stands in block 3. All areas had been prescribed burned 3 years prior to study establishment.

Each treatment unit consisted of a core area of 12.25 ha and a surrounding 20-m buffer, giving a total size of 15.2 ha. Within each treatment unit, there were 36 grid points on 50- by 50-m spacing. The exact configuration varied for the different treatment units to fit site conditions, but a typical layout consisted of a 6- by 6-grid arrangement. Within each treatment unit, there were 10 rectangular 20- by 50-m subplots established between selected grid points. These subplots were systematically located to sample the range of conditions found on treatment units.

Treatments

The plan was to collect pretreatment data during 2000, apply burn treatments to three randomly selected units in each block, and keep the other two units as controls. However, all units in block 2 were burned before pretreatment data collection by an escaped prescribed burn from an adjacent area. Selected units in other blocks were burned as planned in 2001. All units had a 3-year fuel accumulation and were burned during the growing season using ground ignition by hand crews.

Data Collection and Analyses

Before burning, all overstory trees [> 10 cm in diameter at breast height (d.b.h.)] were sampled on the 20- by 50-m subplots. Stand structure and composition were determined by recording species, d.b.h., status (live or dead), total height, height to live crown, height to dead crown, and crown condition. The entire treatment unit was surveyed at least three times per year to track tree mortality. Species, d.b.h., height, and cause of mortality were collected for recently dead trees.

Understory fuel, which is composed of grasses, forbs, and shrubs, is a very significant component of the total fuel in flatwoods. Amounts were determined by clipping from a 1- by 1-m area from a randomly selected location in each 20- by 50-m subplot. Litter samples, which included 1-hour and 10-hour timelag fuels, then were collected from the same area. All material was bagged by type, dried at 85 °C, and weighed. This was done at the end of the growing season before and after burns.

Just before each burn, samples of live shrubs, palmetto, grass, 1-hour litter (dead foliage and twigs 0.01 to 6.0 mm), and 10-hour litter (twigs 6.01 to 25 mm) were collected adjacent to 10 randomly selected grid points in a burn unit. These samples were sealed in plastic bags, weighed, dried, and reweighed to determine fuel-moisture content. Rate of fire spread was determined by recording the time it took fire to burn across a treatment unit. Flame heights were estimated across the unit using grid point poles of known height. Following prescribed burn treatments, data for crown scorch height, live crown height, and total tree height were collected from each 20- by 50-m subplot.

Crown scorch data were compared between blocks with analysis of variance. Tree mortality in percent was transformed using the square root of arcsine. This transformed value was analyzed using pretreatment annual mortality rate as the covariate. Differences in pretreatment fuel loadings were determined by analysis of variance and posttreatment by analysis of covariance using pretreatment values as the covariate. Because there were no pretreatment data for block 2, these analyses were done for blocks 1 and 3 only.

RESULTS

Study areas had open savanna stands typical for this region, as shown by the low stocking and basal area (table 1). The average diameter of trees in the old plantation on block 1 was slightly smaller, which resulted in a lower basal area. Stocking was significantly higher in block 3, because two treatment units averaged nearly 75 trees/ha.

Prescribed burns were predominately head fires, although some flank fires were set along control lines or resulted from shifting wind directions (table 2). Temperatures were relatively high, while relative humidity and windspeeds were moderate. Flame lengths were moderate for all burns, but rates of spread were quite rapid and intensities high in

Table 1—Characteristics of pines > 10-cm d.b.h. on study sites at the Myakka River State Park, FL

Block	D.b.h.	Height	Basal area	Height to live crown	Density
	cm	*m*	*m^2/ha*	*m*	*trees/ha*
1	23.2	16.0	1.6	11.2	38
2	26.8	14.8	2.2	—	38
3	27.9	15.8	3.2	10.2	56

D.b.h. = diameter at breast height.
— = no data collected prior to burning.

both blocks 1 and 3. The drought index ranged from low for block 1 to moderate for block 3. Block 1 was burned during a brief dry period following 2 months of frequent rainfall. The old firelines still contained pockets of standing water on the day of the burn. Conversely, blocks 2 and 3 were burned a few days after some significant rainfall that followed a long dry period. Fuel moisture levels for most fuels were slightly lower in block 3 (table 3).

At the end of the growing season before burning, fuels were dominated by litter and saw palmetto on both burn and control units (table 4). Live shrubs also contained a moderate level of potential fuel, while dead shrubs and grass were minor components. The only significant difference between pretreatment conditions was that control units had more dead shrubs on average than those units assigned to receive burn treatments. One growing season after the burns, litter and saw palmetto were significantly lower on burned treatments. Dead shrub fuel increased following burning, and it appears that live shrub fuel was decreased, but the change was not significant. Total fuel loads were less on burned areas than on the controls.

Crown scorch varied by location within blocks. In block 1 the least amount of scorch (34 percent) occurred in treatment unit 5, which was the unit with the lowest elevation, and the most scorch (67 percent) occurred in treatment unit 1, which had the highest elevation. In block 2 the units that burned in early afternoon had about twice as much scorch (50 percent) as those that burned in late afternoon (25 percent). In block 3 the most scorch (83 percent) occurred in unit 4; scorch was about the same in units 1 and 5, at 63 percent. Overall, crown scorch was lowest in block 2, intermediate in block 1, and highest in block 3 (fig. 1).

Pretreatment tree mortality was uniformly low across block 3 (fig. 2B), but seemed to increase slightly within two

Table 3—Fuel-moisture levels prior to prescribed burns at study sites in Myakka River State Park, FL

Fuel type	Block 1	Block 3
	- - - - percent - - - -	
Saw palmetto	121	114
Live shrubs	121	123
Grass	87	69
Litter		
Foliage	27	26
1-hour twigs	29	19
10-hour twigs	25	19

Table 4—Understory and forest floor fuel loading before and after prescribed burning or no treatment at Myakka River State Park, FL

	Pretreatment		Posttreatment	
Fuel type	Control	Burn	Control	Burn
	- - - - - - - - - - - - g/m^2 - - - - - - - - - - - -			
Saw palmetto	306a[a]	225a	239b	146a
Live shrubs	132a	137a	138a	74a
Dead shrubs	29b	2a	14a	43b
Grass	44a	84a	35a	25a
Litter[b]	337a	292a	384b	129a
Total	848a	770a	931b	417a

[a] Within a row for each time period numbers followed by the same letter are not significantly different at the 0.05 level.
[b] Litter includes both 1- and 10-hour fuels on the forest floor.

Table 2—Conditions on day of prescribed burns, firing technique, fire behavior, and intensity at study sites at the Myakka River State Park, FL

Block	Date	Temp.	RH	Wind	KBDI	Fires type	Spread rate	Flame length	Fire intensity
		°C	*%*	*kph*			*m/min*	*m*	*kW/m*
1	8/20/2001	32	50	5 – 13	182	Head & flank	18	2 – 3	315
2	7/13/2000	32	65	5 – 8	—	Head & flank	4	1 – 3	70
3	4/6/2001	29	63	5 – 13	399	Head & flank	27	2 – 5	330

RH = relative humidity; Keetch-Byram drought index = a measure of the relative dryness based on precipitation and potential evapotranspiration (Keetch and Byram 1968).
— = no data.

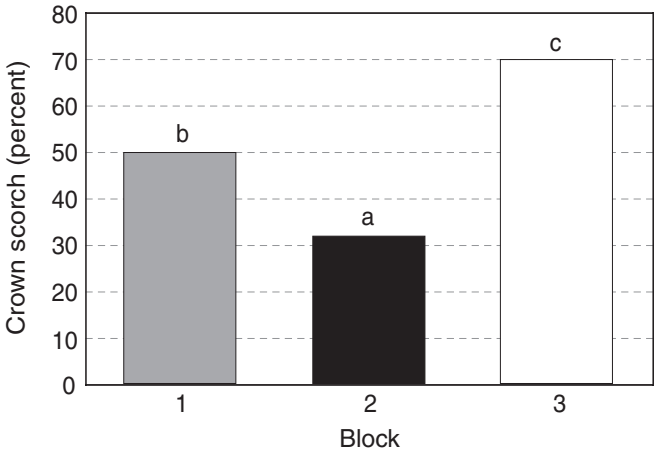

Figure 1—Mean crown scorch from prescribed burns at study sites in Myakka River State Park, FL. Bars with different letters denote significant differences at the 0.05 level.

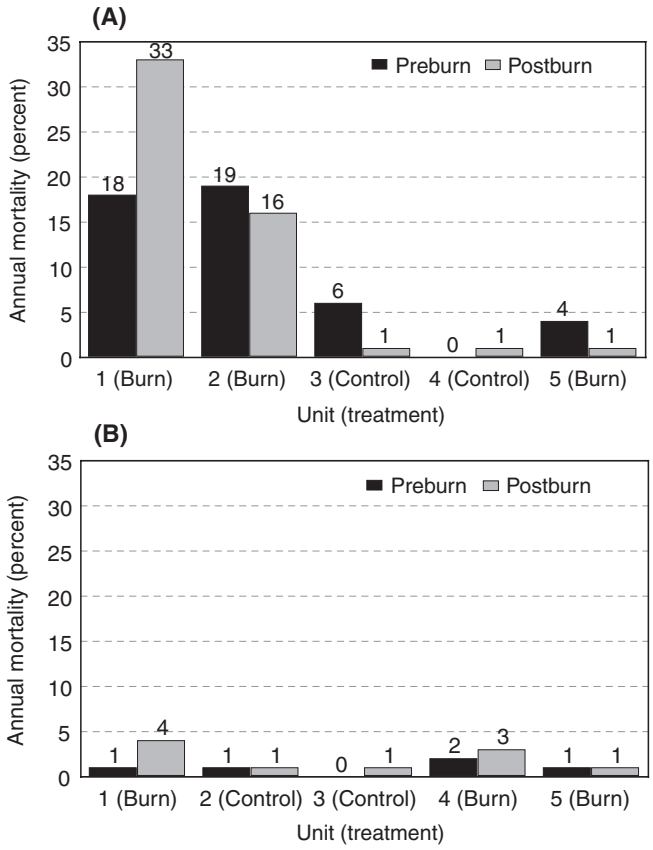

Figure 2—Annual tree mortality by treatment and unit before and after prescribed burns for block 1 (A) and block 3 (B).

treatment units in that block a year after the burns. In block 1, the average annual pretreatment mortality was higher, especially in treatment units 1 and 2 (fig. 2A) than it was in block 3. The year after burning, tree mortality increased in unit 1 but seemed to actually decline slightly in the other two burn units of block 1. For blocks 1 and 3 combined, the year following the burns, there was no significant difference in mean mortality rates between burned and control units.

DISCUSSION

The rates of spread for both blocks 1 and 3 were quite high. Brose and Wade (2002) predicted spread rates of a third to half our rate under drought conditions. This high spread rate resulted from greater windspeeds. Another important factor, however, was likely the location of treatment units relative to initial ignition. Both areas that had a high spread rate were burned by head fires that had considerable distance to develop before they entered the actual burn treatment unit.

Pretreatment fuel loadings for live fuels on all units were very similar to those for north Florida flatwoods systems with a 3-year rough (Brose and Wade 2002). However, 1- and 10-hour fuels in the litter layer were only a third of those for north Florida flatwoods, probably due to a difference in burn efficiency. The growing-season head fires used for recent management burns of the area consume nearly all forest floor material. Because frequent growing-season burning keeps litter from accumulating, there is no duff layer within any of the treatment units. This consumption of the litter layer seems to be the main fuel reduction occurring after our growing-season prescribed burns. Fuel quantities in the living understory were actually higher than those reported by Brose and Wade (2002) 1 year after dormant season burning, but forest floor fuels were about a third of their quantity (129 vs. 336 g/m^2), resulting in essentially the same total fuel load. Some of this difference was likely due to much higher tree density in the north Florida flatwoods, which results in more litterfall but less understory.

Crown scorch was influenced by drought index, location, weather, and firing technique. The highest scorch occurred in a unit of block 3, which was burned during the highest drought index, with a fair wind, and with a well-developed head fire. This combination of conditions produced an intensity of 400 kW/m, the highest intensity of all the burns and the highest crown scorch (83 percent). Although the intensity was quite high, it was less than the 578 kW/m potential intensity for a 4-year rough of this fuel type predicted by Wade and others (2000). The effects of wind and humidity were evident in block 2, where scorch decreased by about half late in the afternoon when wind dropped off and relative humidity increased. Scorch was also reduced because more of the late afternoon units were burned with flanking fires.

Crown scorch is a poor indicator of tree mortality in southern pines (Wade and Johansen 1986). There is generally little mortality until scorch approaches 100 percent. We found no correlation between crown scorch and subsequent mortality. Block 3 had the highest crown scorch but very low mortality, while burned units in block 1 had less scorch but more mortality. Overall, there was not a significant increase in mortality due to burning, but this may change as trees are continuing to die apparently from the combined stress of drought and fire. Inspection the year following burns showed a number of trees that appeared to have died because of the fire in block 1. Just analyzing results following burning, the conclusion would have been a large increase in mortality due to fire. Knowing the pretreatment mortality, however, showed

there was high mortality in the burn units before treatment. This resulted from a prolonged drought, which put stress on the trees, especially those on the highest and driest units; i.e., units 1 and 2. Even though this drought ended with substantial rainfall in the 2 months prior to the burn, the trees probably had lowered carbohydrate reserves and therefore were less prepared to reflush. Although fire likely increased mortality in unit 1 of block 1, a number of these trees would probably not have died in the absence of predisposing drought.

The growing-season burns used in this study were at least as effective in reducing fuel loads as dormant-season burns. Over the long term, growing-season treatment could be even more effective due to a reduction in live woody fuels and an increase in herbaceous components that result from repeated burns (Boyer 1993, Haywood and others 2001, Robbins and Myers 1992). The low-mortality rates in block 3 showed that even with moderate drought levels and very aggressive burning techniques, slash and longleaf pines were able to tolerate growing-season burns. It must be remembered, however, that these stands had been burned on a regular basis in the past and thus did not have a large fuel buildup and had crowns only on the upper third of the stem. Potential tree mortality can be reduced by not burning stands that are already stressed and by avoiding the later portion of the growing season (Robbins and Myers 1992, Weise and others 1990). There is also a potential for growth loss with repeated growing-season burns, but it is too early in this study to evaluate growth rates. Growth loss from burning, however, appears to be age-specific, with growth increases in seedling-age stands (Grelen 1983), some growth loss in sapling to pole-sized stands, and little effect in stands beyond age 25 years (Boyer 2000). Because the trees are 40 to 90 years old and needle loss from crown scorch was not complete, we do not expect any measurable growth loss due to burning.

ACKNOWLEDGMENTS

This is contribution number 37 of the National Fire and Fire Surrogate Network Project and was supported by funding from the U.S. Joint Fire Science Program. Recognition is given to Jason O'Shell and Eric Neiswanger for dedication in treatment application and data collection. A very cooperative park staff accomplished all burning treatments and provided logistical support in addition to the resource base for the study.

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PRELIMINARY EFFECTS OF PRESCRIBED BURNING AND THINNING AS FUEL REDUCTION TREATMENTS ON THE PIEDMONT SOILS OF THE CLEMSON EXPERIMENTAL FOREST

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Abstract—This study is a component of the National Fire and Fire Surrogate (NFFS) Study which is an integrated national network of long-term interdisciplinary research to facilitate broad applicability of fuel impacts. This part of the NFFS study in the Piedmont of South Carolina studied three ways of reducing fuel loads (prescribed burning, thinning, and the two in combination). The objective was to determine the effects of prescribed burning and thinning, alone and in combination, on the following soil components: net mineralization and proportional nitrification, C and N concentrations in the O and A/Bt horizons, and bulk density levels of the A/Bt horizon. Of these variables, prescribed burning caused a significant decrease in proportional nitrification, a decrease in carbon and nitrogen concentrations in the O horizon and a decrease in nitrogen in the A/Bt horizon. The thin only and thin and burn treatments caused an increase in bulk density but there was no effect on net mineralization and proportional nitrification. Thinning did not affect the C:N ratio in the O horizon but fire only reduced it and the thin and burn increased it above all other treatments including the control. These functional changes in site quality measurement changes were relatively small and may be only short term for both thinning and prescribed burning.

INTRODUCTION

Over the last several decades, fire suppression on forested lands has been a standard practice. Lack of fire has given rise to a tremendous increase in forest fuel loads and resulted in many large-scale wildfires. In response, the National Fire and Fire Surrogate (NFFS) Study was established to compare ecological and economic impacts of prescribed burning and mechanical fuel-reduction treatments.

Silvicultural practices, such as prescribed burning and thinning, have been shown to have a wide range of effects on soil properties (Ballard 2000, Johnson and Curtis 2001, Phillips and others 2000). The type of harvesting practice may determine the degree of soil disturbance. Generally, clearcutting has been associated with an increase in total site disturbance and soil scarification (Holmes and Zak 1999, Johnson and Curtis 2001, Olsson and others 1996, Prescott 1997, Walley and others 1996). Single tree selection or other types of less intensive thinning do not seem to have any effects on soil properties (excluding some minor changes in bulk density and acute variations in soil chemistry). Johnson and Curtis (2001) found that, on average, forest harvesting in North America had little or no effect on soil carbon (C) and nitrogen (N). Concentrations of C and N may have a slight decrease within the first year of harvesting but it is not substantial or prolonged (Knoepp and Swank 1997). Whole tree harvesting may result in increased bulk density along with decreases in content of organic matter, total N, sulfur, and exchangeable calcium in upper soil layers (Merino and others 1998). These decreases in organic matter lead to a higher potential for soil erosion.

The effects of prescribed burning on most soil characteristics are dependent upon differing levels of fire intensity and frequency. In general, severe burns have a greater effect on soil properties than less severe burns (Bird and others 2000, Covington and Sackett 1992, Vose and others 1999). Prescribed fire results in substantial nutrient losses through immediate volatilization and fly-ash. Hydrolysis of oxides results in increased soil pH, and the duration of this change is influenced by the soil buffering capacity (Ballard 2000). Severe losses of N are attributed to fire (Grogan and others 2000), and Monleon and others (1997) observed a decrease in net N mineralization after prescribed burning. However, these losses are generally brief, with pre-burn N conditions returning within 1 year (DeLuca and Zouhar 2000, Knoepp and Swank 1997, Monleon and others 1997).

The objective of this study was to monitor the effects of prescribed burning and thinning, alone and in combination, on the following soil components: net mineralization and proportional nitrification, C and N concentrations in the O and A/Bt horizons, and bulk density levels of the A/Bt horizon.

METHODS

Experimental Design

A randomized block design, with blocking on tree size class, was used for this study in order to reduce the variability of tree size classes on treatment effects. Each of the three blocks (replicates) contained four sites (treatment areas) that underwent a specific treatment. The four treatments called for by the NFFS included an untreated control, prescribed fire, thinning, and a thinning followed by prescribed fire.

Study Sites

Twelve study sites, one for each treatment in a replicate, were located on the Clemson Experimental Forest in the upper Piedmont of South Carolina. Elevation ranges from

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

180 to 275 m above sea level. The parent material of the soil consists of phyllites, granites, gneisses, and various schists formed in the late Precambrian to early Paleozoic age (Sorrels 1984). The soil series are Pacolet (fine, kaolinitic, thermic Typic Kanhapludults), Madison (fine, kaolinitic, thermic, Typic Kanhapludults), Cecil (fine, kaolinitic, thermic Typic Kanhapludults), and Tallapoosa (loamy, mixed, semiactive, thermic, shallow Typic Hapludults).

These study sites were chosen on the basis of stand age, size, and management history. Each of the three replicates was dominated by different size classes of trees. Replication 1 was dominated by pulpwood-sized trees diameter at breast height (d.b.h.) (15 to 25 cm); replication 3 was dominated by sawtimber-sized trees (d.b.h. > 25 cm); and replication 2 was a mixture of both pulpwood and sawtimber-sized trees. Trees on all sites were predominately loblolly (*Pinus taeda* L.) or shortleaf (*Pinus echinata* Mill.) pines with a mixture of hardwoods in the under- and mid-story. Each treatment unit was comprised of a 10-ha measurement area and a buffer of at least one tree length surrounding the measurement area. Within the measurement area, 40 permanent grid points were established. Distance and spacing between each grid point was 50 m in one of the cardinal directions.

Treatments

The levels of prescribed burning and thinning were defined by Fire and Fire Surrogate Study protocols to be sufficiently heavy so that if a wildfire occurred on a day with severe weather conditions (80th percentile for wind and relative humidity) during the wildfire season of the Piedmont of South Carolina, February through early April, 80 percent of the overstory trees would survive.

Burning operations were conducted by the Clemson University Department of Forest Resources with assistance from USDA Forest Service personnel. Prescribed fires set in the burn-only treatment areas occurred in the spring of 2001. A moderate fire intensity was desired in order to remove fuels on the forest floor and some vertical fuels. A combination of strip headfires and flanking fires was used on these sites. Flame heights generally ranged from 0.3 to 4 m. Burning was delayed for 1 year in the thin and burn treatment areas due to an increased risk of high fire intensity associated with heavy fuel loads from thinning. Strip headfires were used on these sites, and flame heights generally ranged from 0.3 to 1.2 m.

Thinning operations were conducted by contract in the winter of 2000 and 2001 and were specified as an operator select mechanized thinning. Small, merchantable-sized trees and diseased or insect-infested trees were selected first. Other trees were removed as necessary to provide a residual basal area of 18 m^2 ha^{-1}. Residual slash was spread over the treatment area.

Soil Sampling

Soil sampling took place within ten 20 x 50 m plots randomly installed throughout each treatment area. From each plot, 20 soil samples were taken (the O horizon and the first 10 cm of mineral soil). Twelve samples (six from the O horizon and six from the A and/or upper Bt horizon) were taken for C and N analysis in the center of six 10 x 10-m subplots. Eight samples were taken from the A horizon at the center of four 10 x 10-m subplots and used to determine net mineralization and proportional nitrification rates. Four of these samples were placed back in the ground for a 20-30 day *in situ* period.

Analysis of C and N concentration levels was contracted to Brookside Laboratories, Inc. A Carlo Erba 1500NA C/N analyzer was used to determine concentrations. Mineralization and nitrification samples were analyzed by KCl extraction. Net mineralization and proportional nitrification were calculated as follows:

Net Mineralization =
(Final NH_4 + Final NO_3) – (Initial NH_4 + Initial NO_3).

Proportional Nitrification =
(Final NO_3 – Initial NO_3) / (Initial NH_4 + Net).

"Initial" refers to samples taken at initial retrieval and "Final" refers to samples collected after the 20-30 day *in situ* period.

There were 10 bulk density samples taken per plot (5 on each 50 m side). The samples were taken starting 5 m from the bottom corner along the long axis of the plot and then every 10 m until the fifth sample was taken. This was repeated on the opposite side of the plot. Each of these sample points was offset 2 to 5 m outside the plot to compensate for boundary soil compaction due to extensive research activity.

After collection, we dried the samples at 104 °C for 16 to 24 hours. We then weighed and calculated the bulk density (gms per cm^3) and averaged the 10 readings by plot to determine mean bulk density (both pre- and post-treatment).

Analytical Procedures

To describe the effect of treatment on these soils, we used Analysis of Variance and Covariate Analysis (SAS 1990). The pre-treatment data were used as covariates in order to take into account pre-treatment differences. Bulk density was the only soil component for which covariate analysis was not used due to a difference in pre- versus post-treatment measurement technique.

RESULTS AND DISCUSSION

Bulk Density

The thin-only bulk density average was significantly greater than the control bulk density average, and the thin and burn was significantly greater than all other treatments (table 1). The increased bulk density associated with thinning may have been caused by compaction due to the use of heavy logging equipment. Froehlich (1978) found most changes in bulk density are associated with the first few trips over the ground without regard to pressure. Increases in bulk density across the thin only treatment areas might have been associated with sampling technique if soil samples were taken in a high proportion of skid trails.

Net Mineralization and Proportional Nitrification

There were no significant differences among treatments for net mineralization (table 2). However, there was a signifi-

Table 1—Bulk density in grams per cm^3

Treatment	Bulk density (actual means)[a]
Control	0.801a ± 0.015
Thin	0.874b ± 0.017
Burn	0.822a ± 0.022
Thin and burn	0.955c ± 0.018

[a] Means followed by the same letter within a column are not significantly different at the 0.05 level.

Table 2—Net mineralization and proportional nitrification levels[a]

Treatment	Net nitrogen mineralization	Proportional nitrification
Control	0.118a ± 0.164	0.092a ± 0.024
Thin	0.356a ± 0.146	0.101a ± 0.030
Burn	0.356a ± 0.157	-0.006b ± 0.028
Thin and burn	0.400a ± 0.134	0.070a ± 0.026

[a] Means followed by the same letter within a column are not significantly different at the 0.05 level.

cant difference among treatments for proportional nitrification. Control, thin-only, and thin and burn treatment areas were significantly greater than the burn-only treatment. Monleon and others (1997) observed immediate decreases in mineralization following prescribed burning. However, mineralization returned to pre-treatment levels within 1 year. The reduction in proportional nitrification in the burn-only but not in the thin and burn treatment areas requires some explanation. The fact that the burn in the thin and burn was done a year after the thin does not necessarily explain the difference. We hypothesize that the previous year's thin produced more woody biomass and organic material which the subsequent burn did not remove, thereby retaining adequate levels of N.

C, N, and C:N Ratios (O Horizon)

Losses of C and N were associated with the three treatment types (table 3). C and N concentrations in the thin-only treatment areas and burn-only treatment areas were not significantly different from each other, but both were significantly less than the control. The C and N concentrations in the thin and burn treatment were significantly less than both these treatments and the control. Because of the much reduced N in the thin and burn treatments, the C:N ratio was significantly increased as compared to all other treatments.

The decreases associated with burning may have been caused by volatilization of N and fly ash losses. The decreases associated with thinning may have been a result of mechanical mixing of the existing pre-treatment O horizon into the A/Bt horizons (Ryan and others 1992). The degree of mixing depends upon total site disturbance. In both the burn-only treatment areas and thin-only treatment areas, these decreases may only be short-term and could return to pre-treatment levels within a short time period.

C, N, and C:N Ratios (A/Bt Horizon)

There were no significant differences in the A/Bt horizon among treatments for C, but differences were noted for N (table 4). N was significantly reduced in the burn-only and thin and burn treatment areas. This significant reduction in N fits the pattern of short-term volatilization losses caused by fire noted in previous studies (Grogan and others 2000). We note, however, that N values less than 0.10 percent were reported as 0. N percent averages were determined using all values including the zero data points. Because there were numerous plots with N values of 0, we did not figure the C:N ratio for these data.

Table 3—Carbon, nitrogen, and C:N for the O horizon (percent excluding ratios)[a]

Treatment	Carbon	Nitrogen	C:N
Control	25.01a ± 0.98	1.02a ± 0.04	24.74ab ± 0.66
Thin	20.34b ± 1.00	0.82b ± 0.04	25.90a ± 0.70
Burn	19.92b ± 1.06	0.79b ± 0.04	23.93b ± 0.66
Thin and burn	16.34c ± 0.99	0.50c ± 0.04	33.64c ± 0.67

[a] Means followed by the same letter within a column are not significantly different at the 0.05 level.

Table 4—Carbon and nitrogen for the A/Bt horizon (percent excluding ratios)[a]

Treatment	Carbon	Nitrogen
Control	2.38a ± 0.14	0.11a ± 0.01
Thin	2.17a ± 0.14	0.09ab ± 0.01
Burn	2.25a ± 0.12	0.07b ± 0.01
Thin and burn	2.07a ± 0.12	0.03c ± 0.01

[a] Means followed by the same letter within a column are not significantly different at the 0.05 level.

CONCLUSIONS

In the short term, the functional site quality measurements on various soil parameters were impacted by thinning and burning. Specifically, fire reduced proportional nitrification, N in the O and A/Bt horizons, and C concentration in the O horizon. Fire did not have an effect on bulk density. Thinning alone had no effect on proportional nitrification, but a reduction on C and N in the O horizon was observed. An increase in bulk density values was associated with thinning. Thin and burn in combination also increased bulk density, reduced C in the O horizon and reduced N below all other treatments in both the O and A/Bt horizons.

Together, the fuel reduction treatments of fire, thinning and the two in combination demonstrate what we might expect from these disturbances in the short-term. Fire reduces C and N especially in the O horizon because of its oxidation of the C and volatilization of the N. We might reasonably expect little effect on bulk density since fire generally has no mechanism to alter this. The fact that thinning did reduce C and N in the O horizon may be explained by the mixing of the O horizon with the mineral soil and the resulting dilution. The subsequent and further significant reduction in C and N due to the combination treatment reflects the apparently additive effects of both treatments.

We note that these effects are not unusually great in magnitude. That is, it is quite probable that pre-treatment levels of both C and N will return in a relatively short time. Furthermore, despite the statistical significance of these effects, the actual values are still within the range of normal Piedmont forest ecosystems. It is doubtful, even if these effects were prolonged, whether there would be any effects on long-term forest productivity. Given that the major intent of this research is to test the value of these fuel reduction methods on a variety of sites nationwide, we conclude, based on these preliminary data, that both are viable methods which have little if any deleterious effect on Piedmont forest soils even in the short-term. As long as these fuel reduction operations are conducted responsibly and in accordance with accepted guidelines as was done in this study, both prescribed fire and thinning appear to be reasonable options which could significantly reduce fuel loads and not damage the soil resource.

ACKNOWLEDGMENTS

This is Contribution Number 35 of the National Fire and Fire Surrogate Project (NFFS), funded by the U.S. Joint Fire Science Program.

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RELATIONSHIP BETWEEN PALMER'S DROUGHT SEVERITY INDEX AND THE MOISTURE INDEX OF WOODY DEBRIS IN THE SOUTHERN COASTAL PLAIN

James D. Haywood, Richard H. Stagg, and Allan E. Tiarks[1]

Abstract—After the 1998 through 2000 drought in Louisiana, some prescribed burns had uncommonly severe fire behavior. A significant portion of the consumed fuels most likely were larger material normally unavailable for burning. Therefore at sites in Louisiana, Mississippi, and Texas, we studied the relationship between Palmer's Drought Severity Index (PDSI) and the drying rate of 3- to 12-inch-diameter woody fuels, expressed as resistance of fuel moisture to electrical current in kiloPascals. Woody fuels dried as drought severity increased. Once the drought abated in November 2000, fuel moisture indexes rose but not as quickly as PDSI. Although there is a general relationship between drought condition and drying of large-diameter fuels 1 year after the drought ended, large fuels had not sufficiently rewetted and remained available for burning in the event of a wildfire or prescribed burn.

INTRODUCTION

After the 1998 through 2000 drought in Louisiana, some prescribed burns became uncommonly severe and monitoring techniques, such as the Keetch-Byram Drought Index (KBDI), normally used to predict fuel moisture conditions did not predict this behavior (Keetch and Byram 1968). We suspected that a significant portion of the consumed fuels came from fuel classes not normally ignited in prescribed burns. For example, in April 2001, a prescribed burn within a natural longleaf pine (*Pinus palustris* Mill.) forest generated a Byram's fire intensity (from Brown and Davis 1973) of 447 Btu per second per foot. This fire consumed 650 pounds per acre of living herbage; 540 pounds per acre of living stems < 0.25 inches in diameter; 9,410 pounds per acre of dead fuels < 0.25 inches in diameter; 720 pounds per acre of dead fuels between 0.25 and 1 inch in diameter; and 1,130 pounds per acre of dead fuels between 1 and 3 inches in diameter. Although the conditions were within prescribed KBDI values, this fire intensity was nearly nine times the recommended level of 50 Btu per second per foot and approached uncontrollable intensities (Deeming and others 1977).

Palmer's Drought Severity Index (PDSI) identifies extended periods of unusual moisture conditions compared with seasonal norms and serves as a generalized indicator of the total environmental moisture supply (Louisiana Office of State Climatology 2001). It reflects the overall hydrologic status of a region and is particularly useful for evaluating the potential for development of prolonged regional droughts. PDSI may, therefore, be a better predictor of moisture trends in large-diameter fuels because these fuels do not gain and lose moisture with daily changes in moisture conditions (Deeming and others 1977). PDSI measurements, calculated continuously by the State Climatology Services, are also readily available.

We decided to test prediction of moisture trends for 3- to 12-inch-diameter woody fuels based on trends in PDSI. We plotted PDSI against fuel moisture to determine if such a relationship existed on three sites in the Lower Coastal Plain of Louisiana, Mississippi, and Texas.

MATERIALS AND METHODS

Study Areas

The National Long-Term Soil Productivity (LTSP) study is a joint effort between the U.S. Department of Agriculture, Forest Service, National Forest System and Forest Service Research (Powers and others 1990). We used three LTSP installations on the Palustris Experimental Forest, Rapides Parish, LA; DeSoto National Forest, Jones County, MS; and Davy Crockett National Forest, Trinity County, TX. The Texas site has the driest long-term climate and the Louisiana and Mississippi sites have similar annual precipitation.

Wood Samples

A 43-year-old loblolly pine (*P. taeda* L.) stand on the Palustris Experimental Forest, Rapides Parish, LA, was the wood source. This stand was planted at 6- by 6-foot spacing in 1955. The stand was never thinned, so mortality was high in recent years. Because of dense spacing, the trees had little taper, and the live crown ratio was 25 to 30 percent. At age 40, the average diameter at breast height (d.b.h.) (diameter at 4.5 feet above ground line) of all live trees in the stand was 9 inches, and the average height was 74 feet.

There were 21 trees in the 12- to 14-inch d.b.h. class, and the first live limb was usually > 49 feet above the ground. From this group, three trees with straight boles and few dead limbs below 39 feet were randomly selected as source material. After felling, 3.2-foot long, 12-inch-diameter logs were cut from the main stem of each of the three trees (table 1); a 12-inch-diameter log exceeds the size for 1,000-hour time-lag dead fuels (Deeming and others 1977). Limb material was simultaneously collected from the same trees. The limb samples averaged 3.3 feet long and 4 inches in diameter and were taken from a primary limb. Limb sizes fell in both the 100-hour and 1,000-hour time-lag dead fuel classes (table 1).

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Table 1—Limb and log weights and dimensions for the three study sites in Louisiana, Mississippi, and Texas.

Classes	Location	Weight	Inside-bark diameter at the upper end of the section[a]	Inside-bark diameter at the lower end of the section[a]	Length
		pounds	- - - - - - - - - - - - - - - - *inches* - - - - - - - - - - - - - - - -		
Limbs	Louisiana[b]	9.7	2.9	2.6	39.8
	Mississippi[c]	23.6	4.6	4.2	39.4
	Texas[c]	37.8	5.6	5.2	39.2
Logs[d]	Louisiana	171.5	11.7	11.8	38.1
	Mississippi	158.7	11.6	11.5	39.1
	Texas	162.8	11.7	11.7	39.0

[a] The upper and lower ends of the logs were also the upper and lower ends in the standing tree. The lower end of the limb was the one closest to the tree bole.
[b] The limbs in Louisiana are within the 100-hour time-lag dead fuel class (Deeming and others 1977).
[c] The limbs in Mississippi and Texas are within the 1,000-hour time-lag dead fuel class (Deeming and others 1977).
[d] All logs exceed the 1,000-hour time-lag dead fuel class in size (Deeming and others 1977).

Placement of Wood Samples at Field Sites

Both a limb and log from the same tree were randomly selected, transported from the 43-year-old loblolly pine stand, and placed within the adjacent mature pine stand at each LTSP installation. In Louisiana, the mature stand was a 45-year-old loblolly pine plantation that originated from direct seeding in 1953. At age 37, it was thinned to a residual basal area of 65 square feet per acre. In Mississippi, the mature pine stand was a 63-year-old mixed stand of slash pine (*P. elliottii* Engelm.) and longleaf pine. The slash pines had been planted in 1935. The longleaf pines were residual trees or postplant volunteers. In Texas, this was a natural mixed stand of loblolly, longleaf, and shortleaf pine (*P. echinata* Mill.) between 60 and 80 years old.

Measurements

At each location, a Watermark™ sensor was embedded in the middle of each limb and log to eliminate edge effects on moisture conditions (fig. 1). The sensors are designed to estimate soil water tension by measuring the resistance to electrical current. Using the calibration curve for soil, the measurements were converted to kiloPascals (kPa) as an index of the water content of the log. While not calibrated for measuring water content of wood, the sensors have the advantage of being relatively stable over the course of the experiment. In addition, calibration curves between measurement parameter and water content of wood would have continually changed because wood decays rapidly in the southern environment. An Easylogger automatically recorded the data, which ranged from 14 kPa (wet) to 170 kPa (dry).

Resistance readings were taken from April 1998 through December 2001 at the Louisiana and Texas sites. At the Mississippi site the EasyLogger was not working from

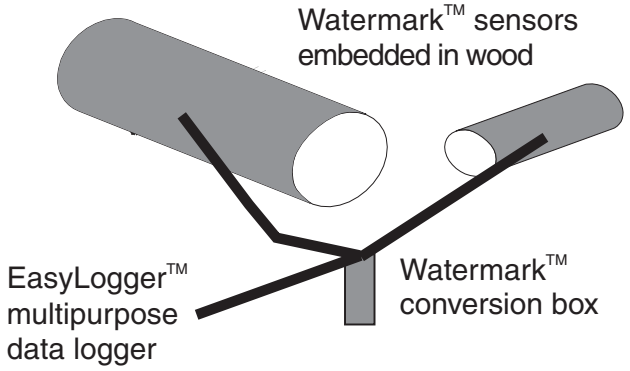

Figure 1—Schematic of the limb and log in the field; a Watermark™ sensor is embedded in the center of each piece of wood.

September through December 2001. For each site, numerical PDSI values were taken from the Southern Regional Climate Center databases for April 1998 through December 2001. The climate divisions for the LTSP sites are Division 5 – Central Louisiana, Division 9 – Southeast Mississippi, and Division 4 – Northeast Texas (Louisiana Office of State Climatology 2001).

Data Presentation and Analysis

For each site, the PDSI data were graphed alone (fig. 2) and in combination with the resistance readings for each limb and log (figs. 3 and 4). To align the data so the x,y intercept would be the driest value for both the PDSI and the moisture index, the resistance data were inverted (1/kPa) in figures 3 and 4. Regression equations were developed to examine the relationship between 1/kPa and time and PDSI ($\alpha = 0.05$).

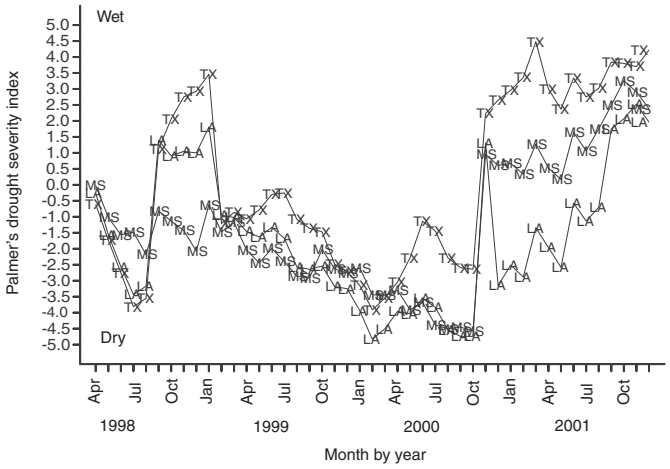

Figure 2—Changes in Palmer's Drought Severity Index for the Louisiana, Mississippi, and Texas sites over a 45-month period from April 1998 through December 2001.

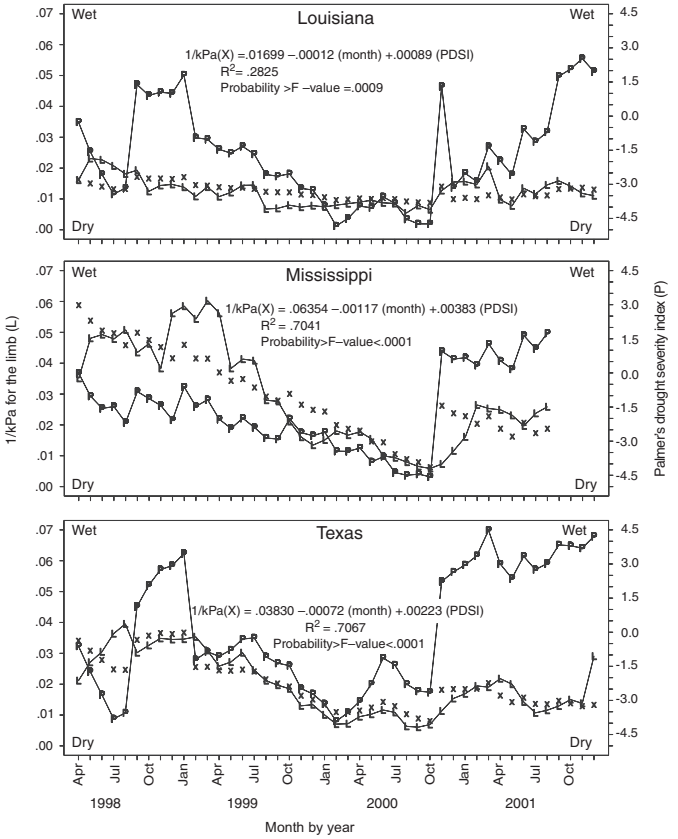

Figure 3—For each limb, monthly changes in 1/kPa (L), predicted 1/kPa (X), and Palmer's Drought Severity Index (P). In the prediction equation for 1/kPa, month is expressed as a numerical value from 4 (April 1998) through 48 (December 2001). Numerical Palmer's Drought Severity Index values were taken from the Southern Regional Climate Center databases.

RESULTS

At all three sites, a drought developed in early 1998 (fig. 2). The drought steadily worsened through October 2000 at the Mississippi site. In Louisiana and Texas, the drought was relieved by fall 1998 but reintensified in early 1999. From early

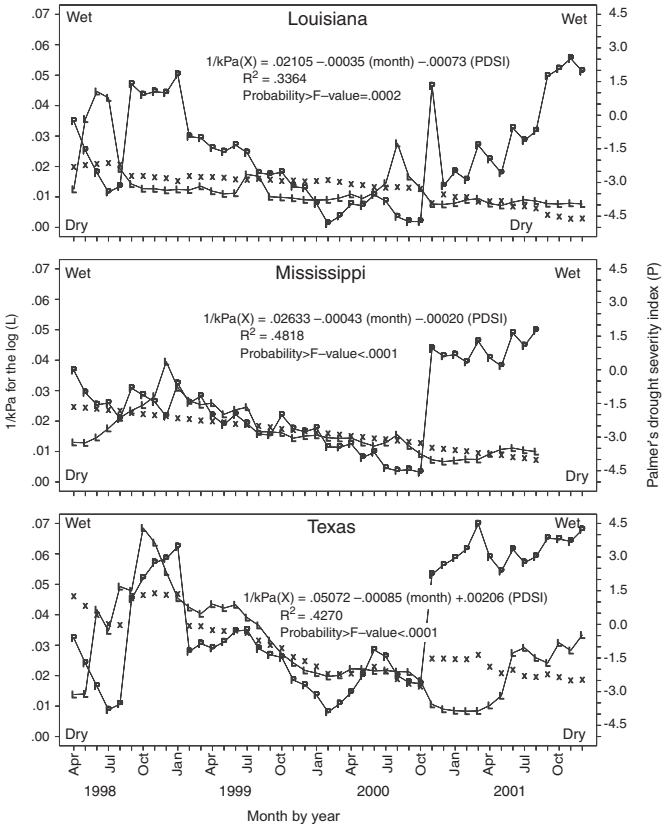

Figure 4—For each log, monthly changes in 1/kPa (L), predicted 1/kPa (X), and Palmer's Drought Severity Index (P). In the prediction equation for 1/kPa, month is expressed as a numerical value from 4 (April 1998) through 48 (December 2001). Numerical Palmer Drought Severity Index values were taken from the Southern Regional Climate Center databases.

1999 it continued to worsen through October 2000 at the Louisiana site. In Texas, a second reversal in the drought began in April 2000, but this reversal was not sustained. On all sites, true drought recovery began in November 2000. The rate of recovery was quickest at the Texas site and slowest at the Louisiana site.

The limb dried in the field in Louisiana from May 1998 through October 2000 and in Texas from September 1998 through October 2000 (fig. 3). The limb dried from May 1998 through October 2000 in Mississippi, but rewetting of the limb in December 1998 interrupted the pattern. The drying pattern was less obvious in Louisiana, where the smallest limb was located (table 1).

We superimposed PDSI and 1/kPa values in figure 3, and there appeared to be a relationship between moisture index (1/kPa) of the drying limb and drought severity. Once the drought began to end in November 2000, the limb moisture index rose and fell with the PDSI value in Mississippi and Texas, although not as quickly as the PDSI value. The amount of rewetting was less in Louisiana than in Mississippi and Texas, and the Louisiana limb was the only 100-hour time-lag fuel in the study (table 1). We suspect this limb, which was also the driest limb at the beginning of the

study, failed to respond measurably to environmental conditions.

In fact, there were significant relationships between the moisture index of the limb and time and PDSI at each study site and for all sites combined (fig. 3). The predicted 1/kPa values for Mississippi and Texas responded more to changes in PDSI than in Louisiana, but for all three sites, none of the changes in predicted moisture was greater than the actual moisture index (table 2). The R^2 values ranged from 0.37 to 0.64.

The log initially became wetter at all three sites (fig. 4). Beginning in July 1998, the log dried rapidly in Louisiana. After October 1998, the moisture level remained fairly constant until it rose temporarily in July and August 2000. In Mississippi, the log dried steadily from December 1998 through March 2001, with some moisture gain thereafter. In Texas, the log dried steadily from October 1998 through March 2001. The log gained moisture after March 2001, and this gain was more obvious than at the Mississippi site.

There appeared to be little relationship between the 1/kPa value of the logs and PDSI in Louisiana and Mississippi, because the log did not rewet after the drought was broken in either State (fig. 4). For Texas, a small gain in moisture occurred 6 months after the drought was broken, a response that would be expected in fuels of this size.

Based on the regression equations, a decreasing, negative PDSI predicted a greater 1/kPa value in Louisiana and Mississippi (table 2). This prediction was counterintuitive, because it would mean the log wetted as the drought worsened, which did not happen (fig. 4). In fact, PDSI had little to do with the drying pattern in either State, because the PDSI values were insignificant in both relationships. The important factor was time in the field. In contrast, the predicted value in Texas responded positively to an increasing PDSI, but still the most important variable was time in the field.

DISCUSSION AND CONCLUSIONS

Wildfires are costly. They place people at risk and destroy wildlife habitat, watersheds, recreational areas, and structural property. Although there is a relationship between drought conditions and moisture of 3- to 12-inch-diameter fuels, these fuels do not sufficiently rewet after drying and may be available for burning in a wildfire or prescribed burn long after droughts end.

While there is a significant relationship between the moisture index and PDSI as the log dried during the drought, there is little relationship after the drought ends. This outcome is not surprising, as PDSI is soil based. Increased rainfall would rapidly infiltrate into the dry soil, increasing the amount of water stored in the ecosystem. However, water is readily shed from a conically shaped log, and so the rewetting cycle of wood is often very slow. Because of this lag in rewetting for many months after the return of normal rainfall, we need to consider the presence and moisture status of large-diameter fuels when fighting wildfires and planning prescribed burns. Also, retention of coarse woody debris is ecologically desirable (Loeb 1999, Spetich and others 2002). To allow time for woody debris to reabsorb water, prescribed burns should be delayed for several years after a prolonged extreme drought.

Large-diameter fuels may accumulate in forests where fire has been absent for decades, in chemically injected stands, and in site-preparation areas where tons of residue woody debris have time to cure. Ways to avoid fuel accumulation

Table 2—Relationship between moisture index, measured by a Watermark™ sensor and expressed in kiloPascals, time,[a] and Palmer's Drought Severity Index[b] for limbs and logs at each of the study sites (Louisiana, Mississippi, and Texas) and for all sites combined

Classes	Study sites	Equation	Root mean square error	R^2	Probability of a greater F-value
Limbs	Louisiana	kPa = 59.949 + 0.646(MO) - 8.892(P)	27.53	0.3663	< 0.0001
	Mississippi	kPa = -19.271 + 2.175(MO) - 11.829(P)	26.32	0.5671	< 0.0001
	Texas	kPa = 4.674 + 2.419(MO) - 10.655(P)	23.13	0.6423	< 0.0001
	Combined	kPa = 17.219 + 1.747(MO) - 8.712(P)	31.46	0.4136	< 0.0001
Logs	Louisiana	kPa = 7.255 + 0.232(MO) + 1.421(P)	20.15	0.5849	< 0.0001
	Mississippi	kPa = 37.445 + 1.834(MO) + 4.860(P)	20.64	0.6195	< 0.0001
	Texas	kPa = 23.983 + 0.868(MO) + 0.803(P)	26.85	0.1885	0.0125
	Combined	kPa = 28.631 + 1.657(MO) - 0.651(P)	29.18	0.3325	< 0.0001

kPa = kiloPascals; MO = time; P = Palmer's Drought Severity Index.

[a] Time is the month (MO) of measurement expressed as a numeric value from 4 (April 1998) through 48 (December 2001).

[b] Numerical *P* values were taken from the Southern Regional Climate Center databases from April 1998 through December 2001 for each of the State's climate divisions where the sites are located: Division 9 - Southeast Mississippi, Division 5 - Central Louisiana, and Division 4 - Northeast Texas.

include repeated prescribed burning or mechanical or chemical treatments to arrest woody plant development.

In our preliminary study, moisture measurements were taken with a soil moisture instrument and with only one limb and log per location. To get a true moisture value for these larger fuel classes, we need to refine this technique and to increase the sample size. Also, we need to study the flammability of larger cured fuels under different moisture regimes.

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EFFECTS OF FUEL-REDUCTION TECHNIQUES ON VEGETATIVE COMPOSITION OF PIEDMONT LOBLOLLY-SHORTLEAF PINE COMMUNITIES: PRELIMINARY RESULTS OF THE NATIONAL FIRE AND FIRE SURROGATE STUDY

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Abstract—As part of the National Fire and Fire Surrogate (NFFS) Study, prescribed burning, thinning, and a combination of burning and thinning were conducted in loblolly (*Pinus taeda* L.) and shortleaf pine (*P. echinata* Mill.) communities in the Piedmont of South Carolina to test the effectiveness of these treatments for fuel reduction. Treatment implementation resulted in an overall reduction of overstory basal area from 28 to 19 m^2 ha^{-1}, with the largest reduction (10.8 m^2 ha^{-1}) occurring in the thin-plus-burn treatment. Stem densities decreased by 6332 stems ha^{-1} in the burn-only treatment, 3330 stems ha^{-1} in the thin-only treatment, and 5288 stems ha^{-1} for the thin-plus-burn treatment. Percent cover of understory vegetation differed significantly between burned plots (burn-only and thin-plus-burn) and unburned plots (thin-only and control). Nonmetric multidimensional scaling indicated three distinct vegetative groups. Identification of distinctive communities created by fuel-reduction treatments will help explain changes that may occur in other components of the NFFS Study, such as fuels, fire behavior, and wildlife habitat.

INTRODUCTION

In forests which historically had short fire-return intervals, several factors over the last century; e.g., fire suppression, farm abandonment, climate change, and past timber harvests, have led to forests that have less spatial heterogeneity, a greater abundance of small-diameter trees, and greater fuel loading (Abrams and McCay 1996, Arno and others 1997, Gilliam and Platt 1999). These changes have resulted in an increased likelihood of wildfire, as well as deterioration of forest health. Fuel reduction can be accomplished through mechanical treatments, burning, or a combination of mechanical treatments and burning, but information about the consequences of these treatments on ecosystem health is lacking (Sierra Nevada Ecosystem Project 1996).

The National Fire and Fire Surrogate (NFFS) Study was established to investigate the ecological, economic, and social consequences of fuel-reduction techniques on vegetation, fuels and fire behavior, wildlife, pathogens, insects, soils, and economics and utilization in these forests with frequent low-severity fire regimes. National sampling protocols have been developed and are followed at all study sites, allowing both regional and national comparisons.

This paper examines changes in vegetation composition resulting from fuel-reduction techniques on one of 13 study sites within the national NFFS. This study site is located in the southeastern Piedmont within a loblolly (*Pinus taeda* L.)-shortleaf (*P. echinata* Mill.) pine community. Results presented here are from the first year following treatment implementation.

METHODS

The study site is located at the Clemson Experimental Forest in the Piedmont physiographic province of South Carolina. The experimental forest covers approximately 7100 ha and is managed by the university for teaching, research, timber production, and recreation purposes. The area is characterized by rolling hills with moderate-to-severe erosion, and soils are primarily of the Cecil-Lloyd-Madison association (Sorrells 1984). Elevation ranges from 200 to 300 m.

Within the Clemson Experimental Forest, 12 treatment areas were selected based on forest type, stand size, stand age, and management history. Loblolly and shortleaf pine communities at least 14 ha in size (comprised of a 10-ha treatment area and a surrounding 20-m buffer) were located using aerial photos and were randomly selected to receive one of four treatments (control, burn-only, thin-only, thin-plus-burn). Treatment areas were blocked by stand age: block 1 consisted of pulpwood-size trees with diameter at breast height (d.b.h.) of 15 to 25 cm, block 3 contained sawtimber-size trees > 25 cm d.b.h., and block 2 had a mix of pulpwood- and sawtimber-size trees. All treatment areas were selected so that time since last thinning or burning was > 10 and > 5 years, respectively.

Ten 0.1-ha sample plots were established within each treatment area. These plots measured 20 by 50 m and were further subdivided into ten 10- by 10-m subplots. Trees (> 10 cm d.b.h.), saplings (< 10 cm d.b.h. and > 1.4 m tall), and shrubs (> 1.4 m tall) were sampled on half of the subplots. D.b.h., status (live, standing dead, dead and down, or harvested), and incidence of beetles or disease were recorded for all trees. Saplings were tallied based on status (live or dead) and size class (class 1—< 3 cm d.b.h., class 2—3 to 6 cm, class 3—6 to 10 cm). Percent cover for each shrub species was estimated within each subplot.

Two 1- by 1-m quadrats were established within each subplot for sampling herbaceous and woody vegetation

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

< 1.4 m tall. Within these quadrats, percent cover was estimated for each species using the following cover classes: 1 = < 1 percent, 2 = 1 to 10 percent, 3 = 11 to 25 percent, 4 = 26 to 50 percent, 5 = 51 to 75 percent, 6 = > 75 percent. Treatment means for basal area, stem density, and percent cover of understory species were analyzed using analysis of variance (ANOVA) with $\alpha = 0.05$.

Implementation of the thinning treatment occurred during the winter of 2000–01. The thinning prescription included selective removal of small, merchantable-sized trees and diseased or insect-infested trees. Other trees were harvested as necessary to achieve the target residual basal area of 18 m^2 ha^{-1}.

Burning occurred in April 2001 and March 2002 for the burn-only and thin-plus-burn treatments, respectively. The prescription for the burn-only treatment called for moderate-intensity surface fires which would result in some overstory mortality. Air temperatures for these fires ranged between 22 and 30 °C with light S. to SW. winds, relative humidity (RH) values between 42 and 56 percent, and 1- to 2-m flame lengths. Strip head fires were used to burn blocks 1 and 2, while a flanking fire technique was used for block 3. For the thin-plus-burn treatments, the prescription was for a low-intensity fire that would kill most of the smaller stems and reduce the midstory. Air temperatures ranged from 18 to 28 °C with light winds from the SE. to SW. RH was between 42 and 55 percent with 1-m flame lengths. Strip head-firing techniques were used for all three blocks.

Nonmetric multidimensional scaling (McCune and Mefford 1999) was used to examine differences in vegetation composition due to treatment effects. Data for shrubs, herbaceous species, and woody vegetation < 1.4 m tall were combined into a single matrix. Rare species, defined as those occurring in only one or two quadrats, were removed from the dataset, and an outlier analysis was performed. Nine quadrats identified as outliers were removed prior to ordination. A secondary matrix also composed of data for shrubs, herbaceous species, and woody vegetation was added into the analysis to examine species correlations with respect to the primary and secondary axes. Ordinations were performed using the "slow and thorough" setting and Sorensen (Bray-Curtis) distance measure in the "autopilot" mode to identify the appropriate dimensionality, choose the best solution for each dimension, and test for statistical significance.

RESULTS AND DISCUSSION

Overstory and Midstory Vegetation

Treatments reduced overall basal area from 28 to 19 m^2 ha^{-1}. The largest decrease in basal area was evident in the thin-plus-burn treatments (10.8 m^2 ha^{-1}), while the burn-only and thin-only treatments were reduced by 6.2 m^2 ha^{-1} (fig. 1). The recent southern pine beetle (*Dendroctonus frontalis* Zimmerman) outbreak in the Southeast influenced mortality rates in both the control plots and burn-only plots. Within one control area, southern pine beetle killed 75 percent of the pines. Burning appeared to weaken the trees, making them more susceptible to pine beetle infestation and mortality. Boyle and others (in press) present southern

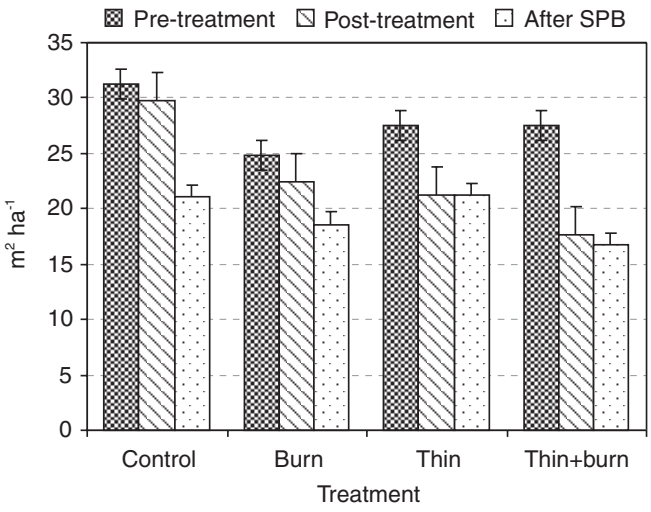

Figure 1—Basal area of overstory trees (d.b.h. > 10 cm) by treatment before and after treatment implementation and southern pine beetle (SPB) effects.

pine beetle impacts for this study. Basal area reduction due to pine mortality was 4.7 m^2 ha^{-1} in the burn-only treatment, 5.6 m^2 ha^{-1} in the thin-only treatment, and 9.4 m^2 ha^{-1} in the thin-plus-burn treatment. Hardwood basal area was reduced 1.5 m^2 ha^{-1} for the burn-only, 0.6 for thin-only, and 1.4 for thin-plus-burn treatments.

Significant reductions in stem densities were evident for the burn-only, thin-only, and thin-plus-burn treatments. The burn-only treatment experienced the largest change in stem density, with density decreasing from 10 192 to 3860 stems ha^{-1} (fig. 2). Most individuals removed were from the 6- and 12-cm d.b.h. classes, which were primarily composed of hardwood species. There was a 70-percent decline in hardwood stems and a 90-percent decline in pine stems in the smallest size class in the burn-only treatment areas. After burning, all stems present in the 6-cm d.b.h. class were hardwood sprouts, except for a few pines in a single subplot that did not completely burn. Stem density in the

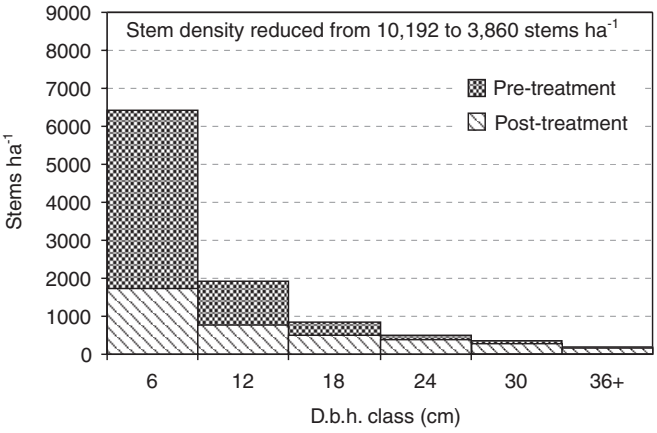

Figure 2—Density of trees before and after treatment in burn-only sample plots.

12-cm d.b.h. class was reduced by about 50-percent, with a 68-percent decrease in hardwood stems and a 47-percent decline in pines. Larger d.b.h. classes also showed some mortality. This treatment had the desired effect of removing some of the overstory as well as significantly reducing the midstory component.

Stem density in the thin-only treatment decreased from 12 536 to 9206 stems ha^{-1} (fig. 3). Number of stems in the 6-cm d.b.h. class dropped from 8870 to 6272 stems ha^{-1}. Hardwood saplings in this size class declined 29 percent, and pine stems were reduced by 32 percent. The number of stems in the 18 to 36+ cm d.b.h. class was reduced by 30 percent, opening the overstory while leaving a fairly dense midstory.

Overall stem density for the thin-plus-burn treatment declined from 10 350 to 5062 stems ha^{-1} (fig. 4). Stems in the 6-cm d.b.h. class were reduced from 6464 to 3026 stems ha^{-1} (hardwoods declined 51 percent and pines were reduced by 88 percent). For the 12-cm d.b.h. class, stem density was reduced by half, from 1654 to 850 stems ha^{-1}. The thin-plus-burn and burn-only treatments had about the same number of individuals in the 6-cm d.b.h. class prior to treatment. Prescriptions for a more intense understory fire in the burn-only treatments reduced stem density in the smallest size class more than the thin-plus-burn treatment. Significant reductions in both the overstory and midstory were achieved in the thin-plus-burn treatment.

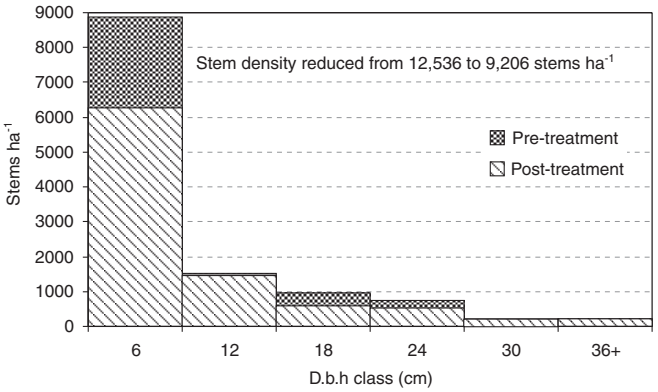

Figure 3—Density of trees before and after treatment in thin-only sample plots.

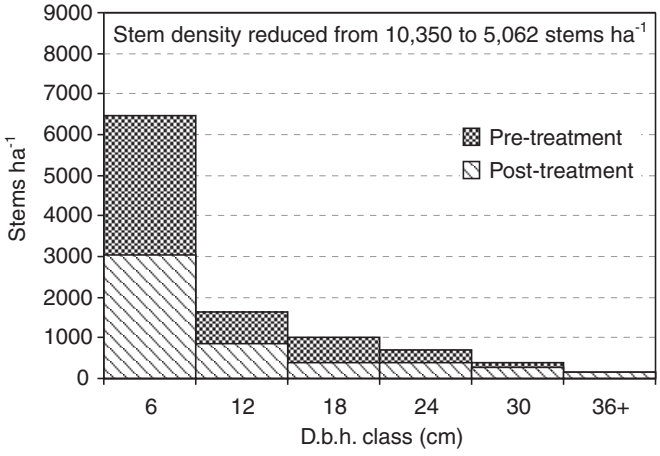

Figure 4—Density of trees before and after treatment in thin-plus-burn sample plots.

Understory Vegetation

Cover of different vegetative life forms < 1.4 m tall varied significantly between burned plots (burn-only, thin-plus-burn) and unburned plots (control, thin-only) (fig. 5). Burn-only plots had significantly greater coverage of forbs, grasses, and trees and less coverage of shrubs and vines than did control plots. The hot fires used for our burn-only treatment reduced overstory basal area and removed significant portions of the midstory, which increased the amount of light reaching the forest floor. They also provided an adequate seedbed for germination of early seral species including fireweed [*Erechtites hieracifolia* (L.) Raf.], other composites, and tree of heaven [*Ailanthus altissima* (Mill.) Swingle]. These burns stimulated sprouting in all hardwoods, particularly oaks (*Quercus* spp.) and hickories (*Carya* spp.).

Compared with untreated controls, the thin-only treatment significantly decreased shrubs, slightly increased forbs and vines, and slightly decreased graminoids and trees (fig. 5). The lack of significant increases in forbs and graminoids and a slight overall reduction in percent cover were unexpected, but were similar to reports by Scherer and others (2000) and Miller and others (1999). Our results may indicate a time lag as understory cover responds to changes in the overstory and/or soil disturbance from thinning machinery (Thomas and others 1999).

In addition to changes in overstory and midstory structure, treatments changed the structure of the forest floor (Waldrop and others, in press). Burning resulted in uniform disturbance of the forest floor, removing the majority of fresh litter and some duff throughout the treatment areas. Disturbance from thinning was more variable, ranging from areas with exposed mineral soil to others with no forest floor disturbance. At least some of the changes in understory vegetation composition can be attributed to these changes in stand and forest floor structure.

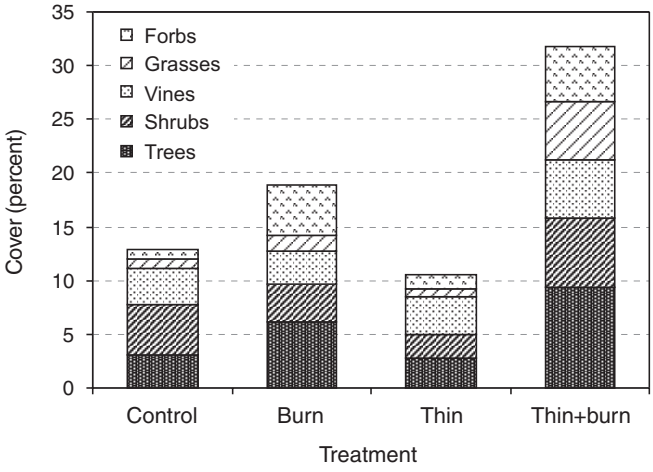

Figure 5—Percent cover of life-form classes for 1-m^2 quadrats.

Thinning and burning significantly increased cover of all life-form classes (fig. 5). Overstory and midstory components were significantly reduced, increasing the amount of light reaching the forest floor. In combination with burning, this increase in light availability appears to improve the effects of physical disturbance caused by harvesting machinery.

Ordinations showed three main groupings (fig. 6): (1) thin-plus-burn plots cluster toward the upper end of both axis 1 and axis 2; (2) burn-only plots are located midway along axis 1 and at the upper end of axis 2; and (3) thin-only and control plots are dispersed along the mid to lower ends of both axis 1 and axis 2. The primary axis appears to be a treatment effect on species richness with a group of plots, primarily controls, with the lowest species richness values on far left. Moving across this axis to the right, the thin-only plots and burn-only plots occupy the same relative space on the primary axis. Those plots at the far right represent thin-plus-burn plots with the highest species richness. Variation along the secondary axis indicates an association with disturbance intensity. Some thin-only plots received severe disturbance, which exposed bare soil, while others were left virtually untouched, thus accounting for the wide dispersion of these plots along axis 2.

Monitoring of changes will continue in subsequent years to determine whether separation between burned and unburned plots continues. We will also examine whether the thin-only plots show differences from the controls. The future trajectories of these communities will depend upon incidence of disturbance (insects, disease, additional fires) over the next few years. Identification of distinct communities created by fuel-reduction treatments will help to explain changes in other components of the NFFS Study; e.g., fuels, fire behavior, and wildlife habitat.

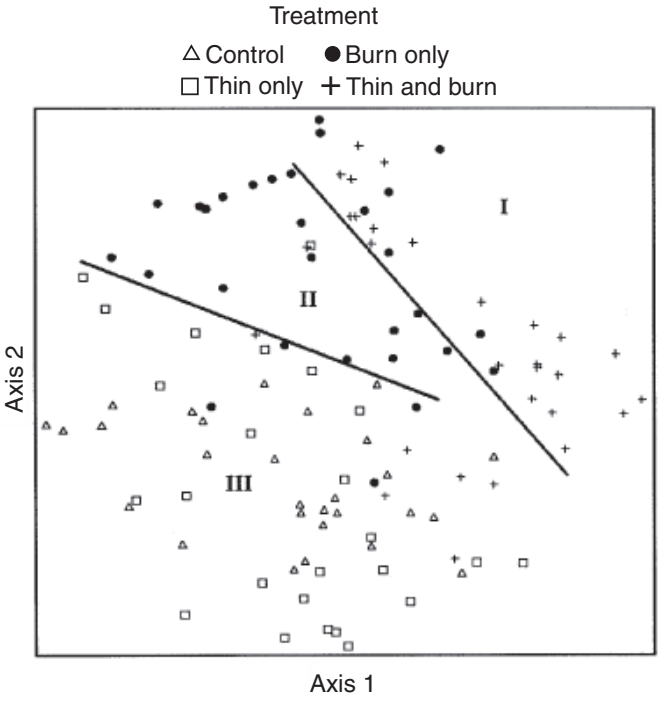

Figure 6—Nonmetric multidimensional scaling ordination for understory vegetation and percent shrub cover.

ACKNOWLEDGMENTS

This is Contribution Number 33 of the NFFS Project, funded by the U.S. Joint Fire Science Program. The authors express their gratitude to the graduate students and summer interns for all their hard work in the field. We specifically thank Sandra Rideout for her input and technical assistance.

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PHYSIOLOGICAL AND GROWTH RESPONSES OF MIDROTATION LOBLOLLY PINE TO TREATMENTS OF FIRE, HERBICIDE, AND FERTILIZER

Emily J. Goodwin, Lisa M. Marino McInnis, Hans M. Williams, Brian P. Oswald, and Kenneth W. Farrish[1]

Abstract—The objectives of this study were to examine the effects of fertilizer and understory vegetation control (herbicide and prescribed fire) on mature tree physiology and to link observed physiological responses with tree growth. Photosynthetic rate (photosynthesis), transpiration, stomatal conductance, stem diameter, and crown area were measured in two midrotation loblolly pine plantations in East Texas. Rates of photosynthesis, E and g_s for the midsummer measurements were significantly reduced by fertilizer treatments on both sites. Drought in east Texas during the last 3 years may have influenced this result. Trees receiving fire at the site with a comparatively more dense live pre-treatment understory exhibited higher rates of photosynthesis; however, prescribed fire had no positive effect on growth. Herbicide treatment significantly increased the change in diameter growth of unfertilized trees at both sites between 1999-2001 by an average of 5 percent, but had no effect on growth of fertilized trees. Increase in diameter growth per unit crown area was significantly greater in unfertilized trees receiving herbicide than in controls.

INTRODUCTION

Intensive silvicultural practices, such as fertilization and competition control, continue to be investigated for potential to induce greater growth in loblolly pine through augmentation or re-allocation of site resources. Chemical control of woody competitors using herbicide has been shown to increase pine tree diameter, basal area, and volume (Bacon and Zedaker 1987, Ezell and others 1997, Hanna 2000, Lauer and others 1993). Prescribed fire has been commonly used in commercial pine plantations to reduce fuel loads and the risk of wildfire. Prescribed fire can increase or decrease growth in mid-rotational loblolly pine, depending on the amount of collateral damage to the trees due to the fire (Wade and Johansen 1986). A positive growth response of midrotation loblolly pine to the use of fertilizer has been documented in various studies (Hanna 2000, Williams and Farrish 1994).

Crown form, size, and function are fundamental determinants of tree growth (Larocque and Marshall 1994a, Rouvinen and Kuuluvainen 1997), but the mechanisms responsible for the effects of silvicultural practices are not fully understood. Larger crown area translates into increased photosynthetic surface area, which can increase stem development and growth (Larocque and Marshall 1994b, Smith and others 1997). Crown growth provides a biological basis for the desired outcome of increased tree growth and optimal use of limited space. Crown growth is therefore a valuable parameter for use in assessing the growth response of trees under various conditions. Some studies have attempted to correlate an increase in site potential through silvicultural manipulation with gains in net photosynthesis (Samuelson and others 2001). To further investigate this potential relationship, this study examined the effects of fertilizer and understory vegetation control on mature tree physiology, and associated observed physiological responses with tree growth.

METHODS

Study Area

The study area consisted of two similar sites located in Cherokee County, TX on land owned by International Paper Company. The first site, Sweet Union (SU), was located within a 45-ha plantation with soils of the Ruston (Typic Paleudalf) and Attoyac (Typic Paleudult) series. The slopes ranged from 3 to 15 percent, and the site index was 71 at base age 25. Prior to planting, the SU site was sheared, windrowed, and burned. The site was then machine planted in 1982 with loblolly pine of unknown, but genetically improved, stock on 1.8 m x 3.7 m spacing (1,495 trees ha^{-1}). In 1998, the site was row-thinned to 833 trees ha^{-1} (basal area of 22 m^2 ha^{-1}).

The second site, Cherokee Ridge (CR), was located within an 80-ha plantation with soils of the Darco (Grossarenic Paleudult), Tenaha (Arenic Hapludult), and Osier (Typic Psammaquent) series. The slopes ranged from 3 to 15 percent, and the site index was 65 at base age 25. Prior to planting, the site received an aerial herbicide application of hexazinone at a rate of 13.6 to 18.1 kg ha^{-1}, followed by a slash disposal aerial burn. The site was hand-planted in 1985 on 1.8 m x 3.1 m spacing at 1,863 trees ha^{-1}, using genetically-improved stock of loblolly pines from two families (3-050-013-CC22L2 and 172-TFS ODHM2). The site was row-thinned and thinned within the rows to 465 trees ha^{-1} (basal area of 13 m^2 ha^{-1}) in 1998.

Five replicates were established in 1999 at each of the two sites. The experimental design was a randomized-block split-plot design. Each replication consisted of 8 subplots each 0.10 ha in size; half of each replicate was randomly chosen for application of fertilizer as the whole plot treatment. Subplot treatments consisted of herbicide, prescribed fire, herbicide and prescribed fire combination and no treatment (control). Each treatment was randomly located

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

within the subplot, and 10-m buffer zones separated subplots. The trees within a 0.04-ha measurement area, in the center of each subplot, were used for all analyses. Each central measurement area contained approximately 35 and 20 trees at the SU and CR sites, respectively.

Vegetation Control Treatments

Herbicide—The herbicide treatment was applied in October, 1999. At CR, the herbicide was a mixture of 4.5 L ha^{-1} Chopper® (imazapyr) (American Cyanamid, Parsippany, NJ), 2.2 L ha^{-1} Accord® (glyphosate) (Monsanto, St. Louis, MO) 11.2 L ha^{-1} Sun-It® II oil (Agsco, Grand Forks, ND), and 76.7 L ha^{-1} water. The same mixture was applied at SU, except that the amount of Accord® was increased to 2.5 L ha^{-1} in an attempt to control a denser understory. To simulate aerial application, the mixtures were broadcast using a CO_2 backpack sprayer with a 3.66 m boom. Competing woody vegetation taller than 3.66 m was injected with a mixture of 100 ml Arsenal© AC (imazapyr) (American Cyanamid, Parsippany, NJ) diluted in 300 ml of water.

Fire—Firelines were installed with hand tools around each burn plot to preserve the 10-m buffer, and firelines were bulldozed around the site as a safety precaution. Prior to burning, ceramic tiles coated with strips of heat-sensitive paint (Tempilaq©, South Plainfield, NJ) were installed at each plot center to allow for an estimate of fire intensities. The subplots were burned in March, 2000 using strip backfires to limit scorch damage to the trees. Each site was burned on a separate day. On the burn days, the relative humidity was 58 percent and 49 percent at the SU and CR sites, respectively. The scorch height (vertical length of the crown in which needle death was evident) was determined for each tagged tree using a clinometer.

Fertilizer—In April 2001, the fertilizer treatment was applied using a crank spreader (Ev-N-Spred® Model 3100, Bristol, TN). Diammonium phosphate (DAP) and urea were applied at a rate of 224 kg ha^{-1} N and 28 kg ha^{-1} P, respectively. These rates were considered standard for operational fertilization in the region. Each site was fertilized on 2 successive days.

Measurements and Statistical Design

Physiology—Three trees per subplot were randomly selected for sampling during the first growing season following treatment applications. Branches in the upper one-third of the south-facing crown were excised using a 12-gauge shotgun. During the summer 2000, the first round of analysis consisted of 1-year-old needles from the first-flush of the 1999 growing season. Winter 2001 sampling consisted of two samples per plot, examining first-flush needles that expanded during the 2000 growing season. Summer 2001 testing used two samples per plot and included measurements of the current flush as well as fully expanded needles from the first-flush of the 2000 growing season.

Net photosynthesis, transpiration, and stomatal conductance were determined using six needles from each sample tree within 5 minutes of separation to minimize the influence of detachment (Samuelson 1998). Measurements were taken in the field with an infrared gas analyzer (Li-6400, LI-COR, Lincoln, NE, USA). An LED light source provided saturating irradiance at 1,600 μmol $m^{-2}s^{-1}$; CO_2 (400 μmol mol^{-1}) and humidity (50 to 60 percent) were controlled within the needle chamber. Midday measurements were taken from 11 a.m. to 3 p.m.

Treatment effects were tested using an analysis of variance (ANOVA) for a randomized block design (SAS Institute, Cary, NC). Results were considered significant at $\alpha = 0.10$ acceptance level. Tukey's multiple range test was used to examine mean differences.

Tree growth—Baseline outside bark diameter at breast height (d.b.h.) measurements were made on each tagged tree in each measurement plot in July, 1999. The trees were remeasured in December 2000 and in December 2001. For each tree, the increase in diameter growth ("%T") was expressed as follows:

$$\%T_{2001} = [(\text{d.b.h. in } 2001)^2/(\text{d.b.h. in } 1999)^2] \times 100 \quad (1)$$

The %T value is, in effect, equivalent to a ratio of the basal areas of the trees converted to a percent. Because of the usage of d.b.h.^2 in growth and yield models and various competition indices, the decision was made to use d.b.h.^2 as opposed to d.b.h. alone (Biging and Dobbertin 1992, Ellis 1979, Moore and others 1973, Smith 1987).

In June of 2000, the crown area of each tree was determined from measurements of the length of the longest branch in each cardinal direction. The lengths of the branches between the branch tip and tree stem were estimated by measuring their vertical projection on the ground with an electronic distance meter (Forestor Vertex, Haglof, Sweden) (Farr and others 1989, Larocque and Marshall 1994a, Minor 1954, Peterson and others 1997, USFS 1970). The area of the polygon resulting from the four measurements was calculated, after correcting for the radius of the tree.

To facilitate hypothesis-testing regarding the possible role of the crown in mediating the effect of the treatments on growth, a novel metric ("LT") was formed as follows:

$$LT = [\%T_{2001}]/[\text{crown area}_{2000}] \quad (2)$$

Although past studies have examined tree diameter growth in conjunction with some crown parameter (Binkley and Reid 1984, Curtin 1964, Lamson 1988, Larocque and Marshall 1994b, Sprinz and Burkhart 1987, Strub and others 1975, Waring and others 1980), no studies have characterized the variable in exactly this manner.

Hypotheses that the treatments resulted in greater tree growth per unit of canopy (more effective utilization of canopy) were tested using the LT metric. The Kolmogorov-Smirnov test revealed that the LT data were not normally distributed. Therefore, each of these hypotheses was tested using the Mann-Whitney U test to compare the LT values between the treatments ($\alpha = 0.05$). The comparisons between the control plots and each of the treatment plots were regarded as 3 independent comparisons (control vs. herbicide, control vs. fire, control vs. herbicide + fire). A similar strategy was implemented in the presence and absence of fertilizer at both the SU and CR sites.

RESULTS AND DISCUSSION

Physiology

Summer—Measurements for summer, 2000 were taken in July at the beginning of a series of dry months. Moisture stress compounded the severe drought experienced during 1999 in east Texas. Measurements taken at CR, the drier, sandier site, showed no significant difference between vegetation control treatments; however, a significant difference was shown for fertilizer treatments with unfertilized trees having greater photosynthetic rates, stomatal conductance, and transpiration (table 1). Kleiner and others (1992) found similar results in oak (*Quercus* spp.) seedlings in response to N additions and water stress. It was concluded that physiological performance is not improved by greater nutrition in the oak species used. This may be true for loblolly pine in dry conditions as well.

Higher photosynthetic and transpiration rates were also observed in unfertilized trees at SU for trees measured in the summer of 2000. This site, with its denser understory, had significantly lower photosynthesis in control plots than in fire-only and herbicide plus fire plots. Stomatal conductance and transpiration were significantly lower on control trees than in trees receiving herbicide only and herbicide plus fire (table 1).

The fertilizer trend was again detected in the 2001 growing season measurements. Unfertilized trees had higher photosynthesis, transpiration, and stomatal conductance at both sites (table 2). Fire-only plots had significantly greater photosynthesis, stomatal conductance, and transpiration than herbicide-only and control plots at CR. Because environmental conditions were drier on the day CR was burned, comparatively greater incidence of scorch was observed (table 3). Increased conductance and transpiration rates could be attributed to the scorch effect described in a study by Ryan (2000), in which defoliated ponderosa pine (*Pinus ponderosa* Engel.) had greater stomatal conductance and transpiration.

Winter—Measurements in winter 2001 showed stomatal conductance and transpiration to be significantly greater in fertilized trees at the CR site (table 4). There was higher than average rainfall for east Texas, which may have caused fertilized trees to have less stomatal limitation. Measurements from winter 2001 showed no significant differences in measured physiology at the SU site. SU had similar findings for fertilized plots, with unfertilized trees having greater photosynthetic, conductance and transpiration rates. Studies with *Zea mays* L. have reflected this finding. Wolfe and others (1988) found that rates of decline

Table 1—Means for treatments at the Cherokee Ridge and Sweet Union sites for summer, 2000

Treatment	Photosynthesis		Stomatal conductance		Transpiration	
	$\mu mol\ CO_2\ m^{-2}s^{-1}$		- - $mol\ CO_2\ m^{-2}s^{-1}$ - -		$mmol\ CO_2\ m^{-2}s^{-1}$	
	CR	SU	CR	SU	CR	SU
Fertilizer	3.28a	5.92a	0.0352a	0.0634a	1.62a	2.63a
No fertilizer	4.18b	6.45b	0.0474b	0.0684a	2.15b	2.94b
Fire-herbicide	3.93a	6.51a	0.0441a	0.0727a	2.03a	3.13a
Herbicide	3.84a	6.27ab	0.0415a	0.0708a	1.89a	2.98a
Fire	3.64a	6.48a	0.0392a	0.0651ab	1.77a	2.75ab
Control	3.51a	5.48b	0.0415a	0.0551b	1.84a	2.29b

CR = Cherokee Ridge; SU = Sweet Union.

Table 2—Means for treatments at the Cherokee Ridge and Sweet Union sites for summer, 2001

Treatment	Photosynthesis		Stomatal conductance		Transpiration	
	$\mu mol\ CO_2\ m^{-2}s^{-1}$		- - - $mol\ CO_2\ m^{-2}s^{-1}$ - - -		- $mmol\ CO_2\ m^{-2}s^{-1}$ -	
	CR	SU	CR	SU	CR	SU
Fertilizer	3.78a	2.78a	0.0351a	0.0232a	1.26a	0.70a
No fertilizer	4.42b	3.37b	0.0473b	0.0347b	1.79b	1.08b
Fire-herbicide	4.14ab	2.92a	0.0398ab	0.0272a	1.53ab	0.83a
Herbicide	3.65b	3.19a	0.0362b	0.0329a	1.24b	1.01a
Fire	4.59a	3.15a	0.0478a	0.0273a	1.81a	0.85a
Control	4.00ab	3.03a	0.0408ab	0.0283a	1.52ab	0.86a
Current flush	5.11a	2.74a	0.0565a	0.0375a	2.08a	1.14a
1-year old flush	3.08b	2.38b	0.0258b	0.0199b	0.97b	0.63b

CR = Cherokee Ridge; SU = Sweet Union.

Table 3—Scorch Index for burned plots at the Sweet Union and Cherokee Ridge sites[a]

Site	Treatment	Scorch index
CR	Fire	82.9
	Fire + herbicide	263.2
	Fertilizer + fire	256.3
	Fertilizer + fire + herbicide	283.4
SU	Fire	1.0
	Fire + herbicide	80.8
	Fertilizer + fire	105.3
	Fertilizer + fire + herbicide	160.2

CR = Cherokee Ridge; SU = Sweet Union; E = fertilizer; F = fire; H = herbicide.

[a] The Scorch Index was computed as the sum of the products of percent treatment scorch (percent) and mean scorch height (m) of the treatment plots.

in photosynthetic capacity were greatest in leaves with N additions than those without during a drydown period. It was suggested that early-season expansion caused greater water demands, which lowered gas exchange during the dry period. Walters and Reich (1989) found similar results using American elm (*Ulmus americana*), where high N concentrations increased photosynthetic rates when trees were provided with irrigation but decreased photosynthetic rates when trees were exposed to water stress.

Tree Growth

At CR, no significant increases in diameter growth per unit crown area (LT) were observed (fig. 1). This was unexpected given that increased photosynthetic rate was observed for unfertilized trees at the same site. In addition, the growth increase for trees receiving fire and fertilizer was significantly less than that of controls. This observation is partially supported by the scorch effect theory (Ryan 2000); it is possible that increased transpiration and conductance rates served as a compensatory mechanism for decreased foliar surface area. However, for this theory to be further supported, similar results on herbicide plus fire plots would be expected.

At SU, all combinations of vegetation control produced significantly greater LT values on unfertilized plots, compared to controls (fig. 2). However, no significant differences were observed in fertilized plots. Photosynthesis was higher in unfertilized plots receiving vegetation control than in unfertilized controls. This corresponded to an increase in LT for the same plots at SU. This result supports the conclusion that reduction of the thick understory present at SU (through use of herbicide competition control) could have contributed to increased photosynthetic rate in crop trees. Increased photosynthetic rate may have in turn contributed to the increased diameter growth per unit crown area. Increased photosynthetic rate of crop trees due to reduction in competitors as a result of herbicide use has not been previously reported, although one study reported the opposite effect (Samuelson 1998).

The increased tree growth observed in plots receiving fire can be understood in terms of an increased LT at SU, but not at CR. One explanation relates to overall vertical crown length. No vertical measurements of the crown were made. However, because the CR site was thinned more heavily than SU, the vertical distribution of foliage on trees at CR was generally greater. It is possible that the lower branches of trees at the CR site did not act as the carbon sink that is normally associated with lower pine tree branches. According to Stephens and Finney (2001), photosynthate production varies throughout the crown. It is generally thought that loss of the less efficient lower crown by scorching (which occurred at CR) will reduce the transpiration demand but not photosynthate production because the more-efficient foliage will remain. It was possible that physiological activity occurring in the lower branches of trees at CR significantly contributed to overall growth. A loss of foliage on lower branches as a result of scorch at CR would have been more detrimental to trees. Therefore, when lower branches were defoliated by scorch, growth was significantly reduced at CR but not at SU. Such an effect could not be determined, because samples removed from crop trees for physiological analysis were taken from the upper third of the crown.

Table 4—Means for treatments at the Cherokee Ridge and Sweet Union sites for winter, 2001

Treatment	Photosynthesis		Stomatal conductance		Transpiration	
	- $\mu mol\ CO_2\ m^{-2}s^{-1}$ -		- - - $mol\ CO_2\ m^{-2}s^{-1}$ - - -		- $mmol\ CO_2\ m^{-2}s^{-1}$ -	
	CR	SU	CR	SU	CR	SU
Fertilizer	4.41a	5.81a	0.0475a	0.0448a	1.03a	0.86a
No fertilizer	4.25a	5.72a	0.0441b	0.0496a	0.96b	0.96a
Fire-herbicide	4.49a	5.91a	0.0473a	0.0466a	1.01a	0.93a
Herbicide	4.29a	5.85a	0.0455a	0.0465a	0.99a	0.91a
Fire	4.16a	5.44a	0.0439a	0.0415a	0.97a	0.81a
Control	4.41a	5.85a	0.0466a	0.0541a	1.01a	0.99a

CR = Cherokee Ridge; SU = Sweet Union.

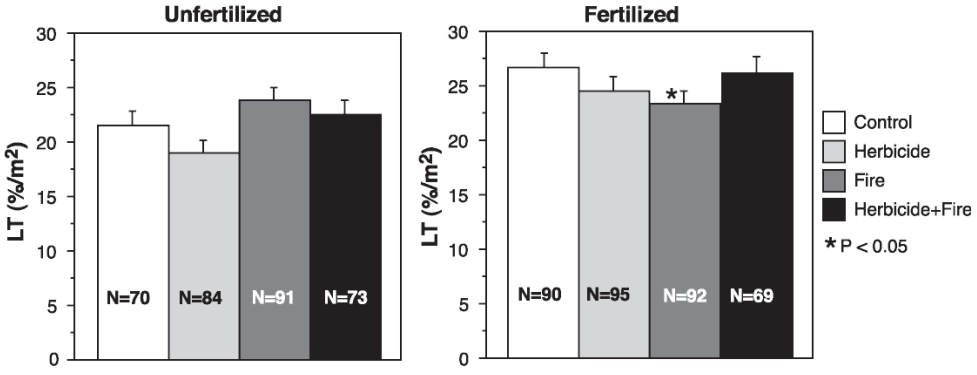

Figure 1—Effect of treatment on loblolly pine tree growth at the Cherokee Ridge site, assessed using LT (reported as mean ± standard error). LT was calculated as the percent ratio of the tree's DBH² to its baseline value (%T, measured in December 2001 and December 1999) per unit crown area (measured in July 2000). All comparisons made were between the respective vegetation control treatment and the control.

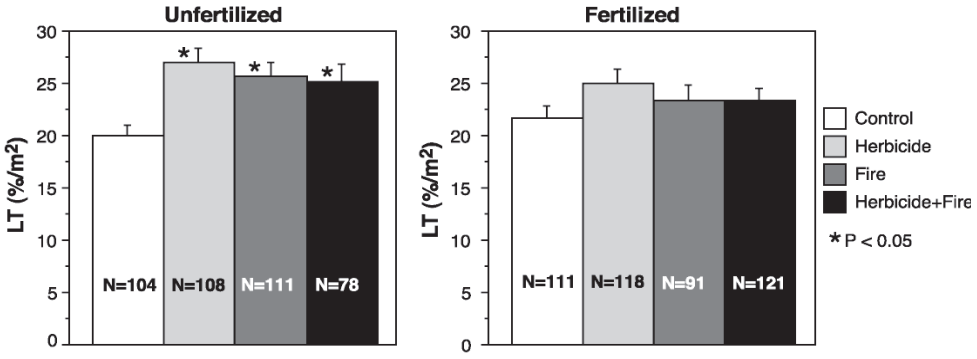

Figure 2—Effect of treatment on loblolly pine tree growth at the Sweet Union site, assessed using LT (reported as mean ± standard error). LT was calculated as the percent ratio of the tree's DBH² to its baseline value (%T, measured in December 2001 and December 1999) per unit crown area (measured in July 2000). All comparisons made were between the vegetation control treatment and the control.

Another possible explanation for the inability of LT to account for growth increases at the CR site could be due to initial crown size. The crown areas of trees at CR were generally larger than those at SU, due to prior thinning operations. It is reasonable to expect that it may take longer to detect differences in larger crowns than in smaller crowns, yet physiological differences were much more readily apparent (i.e. greater photosynthetic rate on unfertilized trees). Because the crowns were measured over a period of 2 years, it is possible that it was too early to observe changes in crown area in trees at CR with larger crowns.

CONCLUSION

Fertilizer failed to significantly increase rates of photosynthesis, transpiration, and stomatal conductance in mature loblolly pine trees at two sites in east Texas. Trees receiving vegetation control in the form of herbicide, fire, or herbicide plus fire exhibited variable physiological responses across the two sites. In terms of tree growth per unit crown area, unfertilized trees receiving herbicide treatment exhibited significantly greater growth increases than control trees. All results were likely impacted by the presence of drought throughout the study.

In situations where water is a limiting resource, fertilizer may cause increased physiological stress in pine trees. This result has been observed in studies involving American elm, oak species, and maize. However, the physiological stressor responsible for the observed responses is yet to be determined.

ACKNOWLEDGMENTS

The authors would like to thank International Paper, the Arthur Temple College of Forestry at Stephen F. Austin University, and the Forest Resources Institute.

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AN EVALUATION OF FUEL-REDUCTION TREATMENTS ACROSS A LANDSCAPE GRADIENT IN PIEDMONT FORESTS: PRELIMINARY RESULTS OF THE NATIONAL FIRE AND FIRE SURROGATE STUDY

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Abstract—The National Fire and Fire Surrogate (NFFS) Study is a large-scale study of the impacts of fuel-reduction treatments on ecological and economic variables. This paper examines prescribed burning and thinning as fuel-reduction treatments on one site of the national study, the southeastern Piedmont. Fuel loads were examined across a landscape gradient before and after treatment. Fuel treatments provided fairly predictable changes to the litter, duff, fine woody fuels, and large woody fuels. Prescribed burning reduced most fuels while thinning tended to increase woody fuels because logging debris was scattered throughout the thinned areas. These patterns varied by landscape position. On mesic sites, burning did not reduce the duff, and none of the treatments changed loading of woody fuels. These results suggest that fuel-reduction treatments may alter numerous components of an ecosystem and that these impacts vary according to landscape position.

INTRODUCTION

Excessive fuel loading has become a concern for forests throughout the United States, particularly in ecosystems where fires were historically frequent. In the southeastern Piedmont, most commercial forest land is in unmanaged nonindustrial private ownerships (Bechtold and Ruark 1988), where fuels are allowed to accumulate. The need for fuel reduction is apparent, but little research is available to guide management decisions. A critical finding of the Sierra Nevada Ecosystem Project (1996) is that silvicultural treatments are readily available that can reproduce the structure of historical forests, but the impacts of these treatments on ecosystem function are largely unknown.

A number of studies document fuel loads after various fuel-reduction treatments in the Piedmont (Geisinger and others 1989, Sanders and Van Lear 1988, Scholl and Waldrop 1999, Waldrop 1997). However, none has attempted to establish the interactions of fuel-reduction treatments with ecological processes and functions. The National Fire and Fire Surrogate (NFFS) Study (Weatherspoon 2000) was established to compare ecological and economic impacts of prescribed fire and mechanical fuel-reduction treatments. Thirteen independent study sites across the United States use identical treatment and measurement protocols. This paper presents preliminary results from one NFFS site in the southeastern Piedmont.

Fuel loads in the Piedmont have a strong relationship to decomposition and position on the landscape (Abbot and Crossley 1982, Ball and others 1993, Crooks and others 1997, Waldrop 1996). Impacts of fuel treatments on ecosystem functions may vary across a landscape by altering microhabitat differently at different landscape positions. However, this hypothesis has never been tested. Jones (1991) developed a Landscape Ecosystem Classification (LEC) system for the Piedmont to identify individual landscape units that primarily represent soil-moisture classes. Each class is a distinct combination of slope, aspect, exposure, and soil water-holding capacity. In this study, our specific objectives are to examine variability of fuel loading in Piedmont pine-hardwood stands across LEC classes, to determine the success of silvicultural treatments for reducing fuel loads, and to determine the interaction of silvicultural treatments and landscape position on fuel loads.

METHODS

The Piedmont site of the NFFS Study is on the Clemson Experimental Forest, managed by Clemson University, in Pickens, Oconee, and Anderson Counties of South Carolina. A wide variety of cover and site types occur on this forest. Topography is strongly a factor of past erosion and ranges from rolling hills to moderately steep slopes. Elevation ranges from 600 to 900 feet above sea level. Most soils are of the Cecil-Lloyd-Madison association, Ultisols with moderate to extremely severe erosion. Entisols and Inceptisols are present but not abundant. Entisols occur along streams and Inceptisols occur on steep slopes. Because of accelerated erosion during the row-cropping era (about 1800 through 1930), rills and gullies are common; as much as 100 percent of the surface soil layer has been removed.

Twelve study sites, one for each treatment area, were selected for size, stand age, and management history. Each site was at least 35 acres to allow for a 25-acre measurement area and a surrounding buffer. Selected sites were judged to be in danger of uncharacteristically severe wildfire due to heavy fuel loads. None had been thinned during the past 10 years, and none had been burned (wildfire or prescribed fire) in at least 5 years. Stand ages varied from 15 to 60 years, but age was used as a blocking factor to reduce variability. Each of three blocks contains four sites (one for each treatment) that

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

are dominated by either pulpwood-sized trees [diameter at breast height (d.b.h.) 6 to 10 inches, block 1], sawtimber-sized trees (d.b.h. > 10 inches, block 3), or a mixture of pulpwood- and sawtimber-sized trees (block 2). All sites were dominated by either loblolly (*Pinus taeda*) or shortleaf (*P. echinata*) pines, with mixtures of oaks and other hardwoods in the understory and midstory.

One of four treatments, as defined by NFFS protocols, was randomly assigned to each treatment area within a block. Treatments include thinning, prescribed burning, thinning followed by prescribed burning, and an untreated control. Levels of thinning and prescribed burning are defined by NFFS protocols to reduce fuels sufficiently so most overstory trees will survive a wildfire. The thin-only treatment was conducted by contract and was specified as a thinning from below. Small merchantable trees and diseased or insect-infested trees were selected first. Other trees were removed as necessary to provide a residual basal area of 80 square feet per acre. Thinning operations were conducted in the winter of 2000–01. Residual slash was spread over the treatment area.

The burn-only treatment was conducted in the spring of 2001 with a prescription designed to reduce fuels and to open the canopy. A combination of strip head fires and flanking fires was used. Flame heights varied from 1 foot to > 10 feet in locations where fuels were heavy.

Thinning on the thin-and-burn treatment was conducted at the same time and with the same contract conditions as the thin-only treatment. Burning, however, was delayed 1 year to the spring of 2002 to allow heavy fuel loads to partially decompose. The prescription for these fires was for intensity to be high enough to remove fuels but not high enough to damage overstory trees. Strip head fires were used with flame heights that ranged from 1 to 4 feet.

Within each treatment area, 40 permanent grid points were established on a 165-foot spacing following cardinal directions. Pre- and posttreatment data were collected at the grid points or locations specified by NFFS protocols. Woody fuel quantities, as well as litter and duff weight and depth, were measured at every grid point.

Litter and duff weight and depth were determined by destructively sampling the forest floor. Samples were randomly selected in areas that represent the full range of forest floor depth on each treatment area. A pilot study using two forest floor samples from each grid point was conducted to determine the sample size need for the remaining areas. Based on the dry weight of litter (L layer) and duff (F and H combined) samples, the sample size equation (Schaeffer and others 1979) predicted that 25 samples per treatment area would estimate the true population mean to within 2 percent. Therefore, one litter and one duff sample were collected at each of the 40 grid points in the remaining treatment areas.

A 1-foot-square wooden frame was used along with a cutter to collect each sample by layer (L and F/H), and each layer was bagged separately. After careful removal of the frame, each layer was measured on each side of the sampled area. Each sample was then washed to remove soil and rocks and dried in an oven set at 85 °C to a constant weight. Litter and duff samples were then weighed in the laboratory to develop regression equations for depth and weight. Resulting equations were used to calculate litter and duff weight on a per-acre basis.

The down dead-woody fuels were measured before and after treatment using the planar intercept method described by Brown (1974). Three 50-foot transects were established approximately 6 feet away from each grid point in a randomly selected direction. This method produced a total of 72,000 feet of fuel transects. Fuels were classified by size class: 1-hour fuels (0 to 1/4 inch), 10-hour fuels (1/4 to 1 inch), 100-hour fuels (1 to 3 inches) and 1,000-hour fuels (3+ inches). One- and ten-hour fuel intercepts were counted along the first 6 feet of the transect and 100-hour fuels were counted along the first 12 feet. Fuels in the 1,000-hour class were recorded by species, diameter, and decay class along the entire 50-foot transect. Fuel counts were converted to weights with equations given by Brown (1974). Statistical analyses of fuel loads were conducted for litter, duff, fine woody fuels (1-, 10-, and 100-hour fuels) and large woody fuels (1,000-hour fuels).

Each grid point in all 12 treatment areas was visited to determine its LEC unit. Landform index (McNab 1993), terrain-shape index (McNab 1989), and depth to the Bt soil horizon were measured. Values were entered into a discriminant function developed by Jones (1991). Equation results indicated which LEC unit best described the area around each grid point. Possible LEC units included xeric, subxeric, intermediate, submesic, and mesic. Fuel loads (litter, duff, fine woody fuels, and large woody fuels) were determined for each LEC unit within each treatment area. Differences and interactions among treatments and LEC units were tested by analysis of variance with mean separation by linear contrast. Differences were considered significant at $\alpha = 0.05$.

RESULTS AND DISCUSSION

Accumulation of litter, duff, fine woody fuels, and large woody fuels will first be presented across LEC units before treatment. Next, treatment effects across all LEC units combined will be presented. Finally, the interactions of treatment and LEC unit will be presented.

Landscape Position Effects on Fuel Loads

Litter accumulation before treatment did not vary among LEC units and averaged 5.5 tons per acre (table 1). Duff accumulation did vary by landscape position, with the least accumulation on the driest and wettest sites. This pattern agrees with an earlier study by Ball and others (1993) who suggested that duff depth was determined by a balance of root production and decomposition rates. On moist sites, decomposition rates are higher than on dry sites, and root production is probably lower in these areas because water is readily available. On xeric sites, decomposition is slower, but root production must be lower due to the poor quality of the site. These results suggest that extra care should be taken when thinning mesic sites or when thinning or burning the xeric sites to prevent soil exposure and erosion.

Table 1—Litter and duff weight across Landscape Ecosystem Classification units before treatment

LEC unit	Litter weight	Duff weight
	- - tons per acre - -	
Xeric	5.3a[a]	5.5b
Subxeric	5.6a	7.3a
Intermediate	5.7a	7.2a
Submesic	5.7a	6.3ab
Mesic	5.3a	5.3b

LEC = Landscape ecosystem classification.

[a] Means followed by the same letter within a column are not significantly different at the 0.05 level.

Accumulation of fine woody fuels varied somewhat across LEC units (table 2). Loading of fine woody fuels tended to be greater on the more moist LEC units, which is probably a result of higher productivity on moist sites. Loading of 1-hour and 10-hour fuels was significantly greater on mesic sites. The larger 100-hour fuels were highly variable, and significant differences were not detected. For total fine fuel loading, the variability of 100-hour fuels masked the differences shown for smaller fuels, so significant differences were not detected.

The implications of these results are somewhat unclear for wildfire management and prescribed burning. Usually, extra care should be exercised in areas with heavier fuel loading. Because these heavy loads were on moist sites, however, fire behavior may not be strongly associated with these differences.

Large woody fuels (> 3 inches in diameter) correspond roughly to coarse woody debris. Loading of these fuels ranged from 4 to 6 tons per acre and did not vary among LEC units (table 2). Coarse woody debris is an important structural component of these ecosystems, contributing habitat for wildlife, insects, and microorganisms. These results suggest that differences in decomposition and productivity among LEC units balance the accumulation of large woody fuels, particularly in the absence of catastrophic disturbances.

Treatment Effects on Fuel Loads

Litter weight did not vary among treatment units prior to treatment and averaged about 5 tons per acre (table 3). After treatment, litter loads followed a fairly predictable pattern. Loading was reduced somewhat by thinning, but burning was necessary to remove the litter layer. Litter weight was significantly lower in burned plots and thin-and-burn plots when compared to controls or thin-only plots.

As with litter, the duff layer was uniform throughout treatment areas before treatment (table 3), with an average of about 7 tons per acre. After treatment, duff weights were highly variable. The only treatment with a significant decrease in duff was the combination of thinning and burning. Even though the mean duff weights for thinning alone and burning alone were not significantly different, the two treatments produced different forest floor structure. Burning removed a portion of the duff over a large area, while thinning removed larger portions of the duff in skid trails but none in undisturbed areas. These differences probably have little impact on fire behavior but may impact nutrient cycling, understory vegetation, and herpetofaunal populations, particularly on mesic sites where herpetofauna are more abundant and duff is thin.

Fine woody fuels did not vary among treatment areas before treatment (table 4). However, they changed dramatically in response to thinning. Loading increased from 2.9 to 4.0 tons per acre as tops were left throughout thinned areas. Prescribed burning did not reduce loading of these fuels. There were no significant differences when comparing the burn-only treatment to the control or when comparing the thin-and-burn treatment to the thin-only treatment. As expected, these results indicate that thinning increases fire risk and fire intensity for some period of time after treatment. A more interesting question will be how long this impact will last and what the implications will be for future fuels management and ecosystem function.

Loading of large woody fuels varied from 4.6 to 5.9 tons per acre before and after treatment, but there were no significant differences among treatments at either time (table 4). Prescribed burning of the intensities used in this study had little impact on larger fuels. Thinning was expected to increase loading in this size class, but variability may have been too high to detect the difference that is shown here.

Table 2—Weights of fine and large woody fuels across Landscape Ecosystem Classification units before treatment

LEC unit	1-hour fuels	10-hour fuels	100-hour fuels	Total fine fuels	1,000-hour fuels	Total woody fuels
			tons per acre			
Xeric	0.27c[a]	1.05b	0.97a	2.29a	5.8a	8.1a
Subxeric	0.30c	1.07b	1.55a	2.92a	6.0a	8.9a
Intermediate	0.33ab	1.16b	1.55a	3.04a	5.1a	8.1a
Submesic	0.30bc	1.10b	1.44a	2.84a	4.3a	7.1a
Mesic	0.41a	1.65a	1.88a	3.94a	5.1a	9.0a

LEC = landscape ecosystem classification.

[a] Means followed by the same letter within a column are not significantly different at the 0.05 level.

Table 3—Weight of litter and duff before and after treatment

Treatment	Litter weight before treatment	Litter weight after treatment	Duff weight before treatment	Duff weight after treatment
		tons per acre		
Control	5.4a[a]	4.9a	7.5a	7.7a
Thin only	5.2a	3.9b	7.0a	5.3a
Burn only	5.0a	1.3c	6.7a	5.1ab
Thin and burn	4.7a	0.8c	6.5a	3.5b

Landscape ecosystem classification (LEC) units combined.

[a] Means followed by the same letter within a column are not significantly different at the 0.05 level.

Table 4—Weight of fine and large woody fuels before and after treatment

Treatment	Fine woody fuels before treatment	Fine woody fuels after treatment	Large woody fuels before treatment	Large woody fuels after treatment
		tons per acre		
Control	2.7a[a]	2.4a	4.6a	4.8a
Thin only	2.9a	4.0b	5.8a	5.9a
Burn only	3.2a	2.1a	5.4a	4.8a
Thin and burn	2.6a	3.4b	5.8a	4.9a

[a] Means followed by the same letter within a column are not significantly different at the 0.05 level.

Interaction of Landscape Position and Treatment Effects on Fuel Loads

Treatment means for litter, duff, fine fuels, and large fuels are shown in figures 1 through 4, respectively, and grouped by subxeric, intermediate, and mesic sites. Xeric sites were not included, because too few of these sites existed in burned stands for analysis. Submesic sites were not shown to improve visual clarity.

Prior to treatment, litter weights did not vary among LEC units (table 1), so an interaction between treatment and LEC unit was not anticipated. The same general pattern of treatment effects on litter loads occurred across all LEC units (fig. 1). Thinning reduced litter weights to some degree, but burning nearly removed the entire litter layer.

Responses of the duff layer to treatments did vary among LEC units (fig. 2). Duff reduction follows the same pattern on subxeric and intermediate sites, but differences occurred on mesic sites. On subxeric and intermediate sites, duff was reduced by both thinning and burning treatments. On mesic sites, however, burning had no impact on the duff layer. This suggests that the duff was too moist to burn on protected mesic sites when it would burn on more exposed drier sites. While the overall objective of treatment is to reduce fuels, protection of the duff on moist sites should

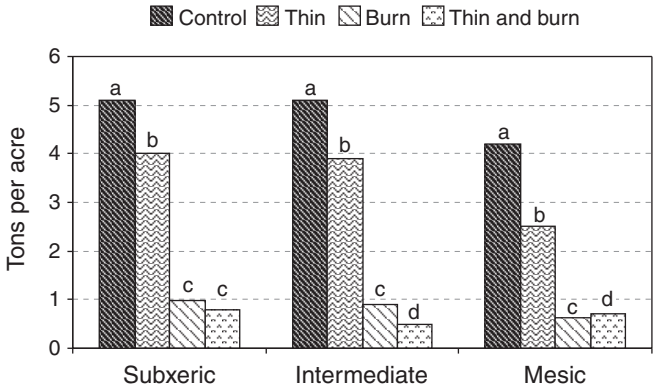

Figure 1—Posttreatment litter weights by treatment and Landscape Ecosystem Classification unit. Means followed by the same letter within a group are not significantly different at the 0.05 level.

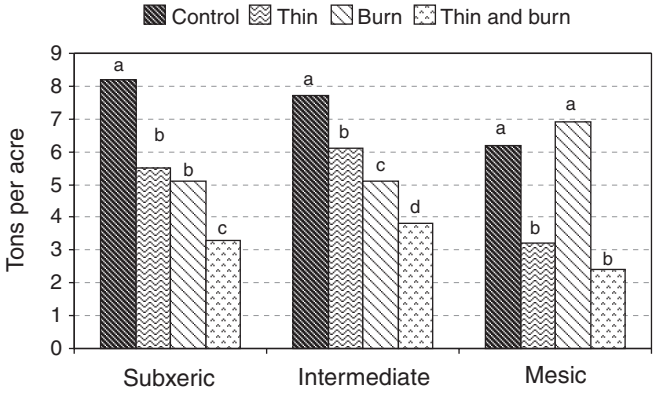

Figure 2—Posttreatment duff weights by treatment and Landscape Ecosystem Classification unit. Means followed by the same letter within a group are not significantly different at the 0.05 level.

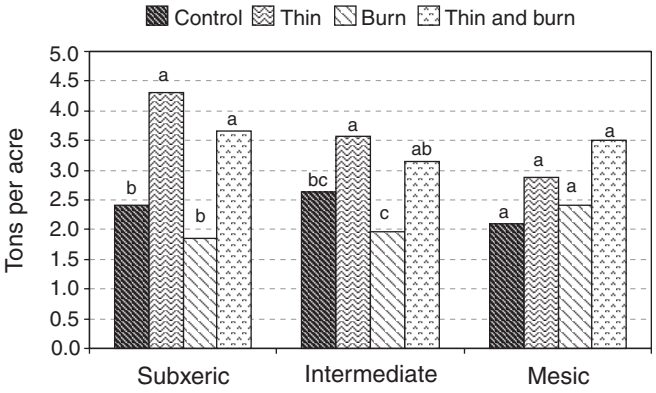

Figure 3—Posttreatment weights of fine woody fuels by treatment and Landscape Ecosystem Classification unit. Means followed by the same letter within a group are not significantly different at the 0.05 level.

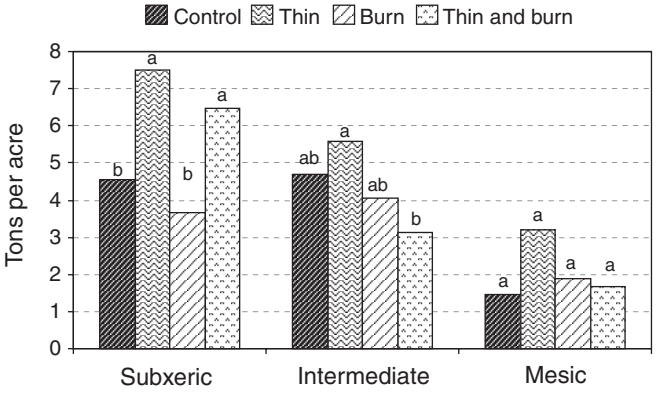

Figure 4—Posttreatment weights of large woody fuels by treatment and Landscape Ecosystem Classification unit. Means followed by the same letter within a group are not significantly different at the 0.05 level.

be considered beneficial for protecting water quality and habitat of numerous organisms.

Loading of fine woody fuels showed a significant interaction between treatment and LEC units (fig. 3). On subxeric and intermediate sites, thinning increased loading of these fuels, and burning reduced loading somewhat. Even though mesic sites had the same general pattern, the differences were not significant. It may be possible that fewer trees were harvested from mesic sites or that the results were too variable to detect differences.

Loading of large woody fuels showed an interaction between treatment and LEC (fig. 4). Fuel loading on subxeric sites followed a predictable pattern, with increases in the thinned and thin-and-burn plots. However, treatment impacts were less pronounced on intermediate and mesic sites. There is a general tendency across sites for lower loading on the more moist sites. Loading of large fuels on control plots was significantly lower on mesic sites than on subxeric or intermediate sites. This difference on mesic sites may be attributed to increased decomposition rates or lack of inputs, possibly due to better tree vigor. Lack of fuel inputs in burned areas was expected, especially on mesic sites where fire intensity would be reduced. The lack of fuel inputs on thinned mesic sites was unexpected. Casual observation of these sites suggests that fewer trees were harvested from those areas. In addition, these areas tended to be at the bottom of slopes so that trees were probably felled uphill. In this case logging slash would have accumulated in other LEC units.

SUMMARY AND CONCLUSIONS

The LEC System proved useful in understanding fuel loading across landscapes. Duff layers were thin on xeric and mesic sites, and loading of 1- and 10-hour fuels was heavier as soil moisture increased. Treatment impacts on fuels followed a fairly predictable pattern. Litter and duff were removed by the thin-only and burn-only treatments, and a greater quantity of both was removed by thinning plus burning. Fine woody fuels were increased by thinning, but burning had little impact. A better understanding of fuel accumulation was achieved by examination of the interactions of treatments and LEC units. Litter and duff were generally reduced by treatments, except that burning on mesic sites had no impact on the duff layer. Thinning generally increased loading of both fine and large woody fuels, except on mesic sites where no additions were observed. This study suggests that, in the short term, wildfire behavior on xeric through intermediate sites would be reduced by prescribed burning but increased by thinning, even in combination with prescribed burning.

Several components of these ecosystems may have been impacted by fuel-reduction treatments. Each treatment is likely to impact microsite weather conditions which will impact fire behavior, habitat for many organisms, and nutrient cycling. Differences of duff structure between thinning and burning may affect insect and herpetofaunal populations, soil fertility, and nutrient cycling. Treatment differences also impact forest structure by adding or removing coarse woody debris. These impacts are likely to impact wildlife habitat and nutrient cycling. Continued monitoring of all variables and treatment areas in the NFFS Study are needed to provide greater insight into ecosystem changes over time.

ACKNOWLEDGMENT

This is Contribution Number 34 of the National Fire and Fire Surrogate Project, funded by the U.S. Joint Fire Science Program.

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IMPACT OF PRESCRIBED FIRE AND THINNING ON HOST RESISTANCE TO THE SOUTHERN PINE BEETLE: PRELIMINARY RESULTS OF THE NATIONAL FIRE AND FIRE SURROGATE STUDY

M. Forbes Boyle, Roy L. Hedden, and Thomas A. Waldrop[1]

Abstract—The southern pine beetle (*Dendroctonus frontalis* Zimm.) is considered one of the most aggressive insect pests in the Southern United States. Resistance to southern pine beetle infestations in southern pines depends largely on oleoresin flow rate and total flow. Treatments, such as prescribed fire and thinning, can be used to reduce stand infestation susceptibility by increasing the vigor of residual pines. This study examines the short-term effect of prescribed fire and thinning on pine vigor and degree of southern pine beetle incidence. Pine vigor and beetle incidence data were compiled during the summer and fall of 2001 during a severe southern pine beetle outbreak. Although there were no significant short-term treatment effects on pine vigor or beetle incidence, 24-resin weight was found to be inversely related to both size of beetle infestations and number of beetles trapped in each stand. Direct relationships found between 24-resin weight and recent 5-year latewood percentages may indicate that increased host vigor is associated with increased area of latewood.

INTRODUCTION

The southern pine beetle (SPB), *Dendroctonus frontalis* Zimm., is the most important insect pest on southern pines in the United States. Infestations generally occur in overstocked stands of slow growing, low vigorous pines. However, during periods of beetle outbreak, all pines become susceptible to an attack (Payne 1980). An increase in the frequency and intensity of SPB outbreaks has been noticed in the past several decades (Price and others 1998). Increases in SPB activity appear to be closely related to changes in forest structure (Hedden 1978). Trends in land use during the past 100 years, such as fire exclusion, conversion of stands to high density pine forests, and frequent cuttings, have led to an increase of stand susceptibility to SPB attack (Cameron and Billings 1988).

Oleoresin flow is the primary tree defense against SPB infestations, and vigorous pines are thought to produce more resin than unhealthy pines (Lorio and others 1995). Reeve and others (1995) found that bark beetles have much greater reproductive success on trees with less resin. As beetles penetrate through the inner bark and expose xylem tissue in order to construct egg galleries, resin acts as a physical and chemical barrier (Payne 1980). Working from the growth-differentiation balance model proposed by Loomis (1932), Lorio (1986) postulated that during times of moderate water stress, resin flow is favored over tree growth, and beetle attack is reduced. Increased host resistance is associated with the transition of earlywood to latewood and the production of new vertical resin ducts (Lorio and others 1990). Until these new vertical ducts are formed, resin flow is limited to the vertical ducts of preceding years.

This study is a component of the National Fire and Fire Surrogate (NFFS) Study. The NFFS examines impacts of silvicultural treatments for fuel reduction on numerous ecosystem components in 13 ecosystems across the country. Silvicultural practices, such as those used in the NFFS, can be used to reduce losses from the SPB by reducing pine density and increasing individual tree vigor (Belanger and others 1993). Thinning has been shown to improve resin flow rates by increasing host crown size (Lombardero and others 2000). The disturbances caused by these silvicultural techniques, however, may cause short-term increases in SPB activity due to short-term adverse effects on tree and stand vigor (Hedden and Belanger 1985). Therefore, this study was conducted to determine the effects of prescribed fire and thinning on the incidence of SPB attack and on host resistance mechanisms.

METHODS

Experimental Design

A randomized block design, with blocking on tree size class, was used for this study in order to reduce the variability of tree-size classes on treatment effects. Each of the three blocks (replicates) contained four sites (treatment units) that underwent a specific treatment. The four treatments called for by the NFFS included an untreated control, prescribed fire, thinning, and a thinning with prescribed fire. Weather conditions prevented the application of prescribed fire within the thinning with prescribed fire treatment units prior to the sampling period for this study. Therefore, two thinned treatments were compared against the prescribed fire and untreated control units.

Study Sites

Twelve study sites, one for each treatment in a replicate, were located on the Clemson Experimental Forest in the Upper Piedmont of South Carolina. These study sites were chosen on the basis of stand age, size, and management history. Each of the three replicates was dominated by different size classes of trees. Replication 1 was dominated by pulpwood-sized trees (d.b.h. 15-25 cm); Replication 3 was dominated by sawtimber-sized trees (d.b.h. > 25 cm);

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

and Replication 2 was a mixture of both pulpwood and sawtimber-sized trees. All of the sites were predominately loblolly (*Pinus taeda* L.) or shortleaf (*Pinus echinata* Mill.) pines with a mixture of hardwoods in the under- and mid-story. Each treatment unit was comprised of a 10-ha measurement area and a buffer of at least one tree length surrounding the measurement area. Within the measurement area, 40 permanent grid points were established. Distance and spacing between each grid point was 50 m in one of the cardinal directions.

Treatments

The levels of prescribed burning and thinning were defined by NFFS protocols to remove sufficient fuels so that if a wildfire occurred on a day with severe weather conditions (80^{th} percentile for wind and humidity) during the wildfire season of the Piedmont of South Carolina - February through early April - 80 percent of the overstory trees would survive. Burning operations were conducted by the Clemson University Department of Forest Resources with assistance from U.S. Department of Agriculture Forest Service personnel. A backing fire was set by hand along the northeast side of the Replication 1 Burn to burn into the southwesterly wind. Strip headfires were set in parallel lines approximately 3 to 5 m apart. A backing fire was set by hand at the northern side of the Replication 2 Burn to burn into the southerly wind. Strip headfires were set in parallel lines approximately 3 to 5 m apart. A backing fire was set by hand along the northern side of the Replication 3 Burn to burn into the southerly wind. Flanking fires approximately 10 m long were set perpendicular to the backing fire, and spot fires were set in areas not covered by the flanking fires.

Thinning operations were conducted by contract in the winter of 2000 and 2001 and were specified as an operator select mechanized thinning. Small, diseased, damaged, or beetle-infested trees were selected first. Other trees were removed as necessary to provide a residual basal area of 18 m^2 ha^{-1}. Residual slash was spread over the treatment area.

SPB Infestations

The presence and absence of SPB were monitored during the late fall of 2000 and 2001. At each grid point of a treatment unit, an ocular estimate of whether trees were infested with beetles was recorded. Signs of infestation included needle color change, pitch tubes along the bole of the tree, and wood dust in the crevices of bark or around the base of the tree.

The boundaries of beetle-infested spots from years 2000 and 2001 were mapped in February of 2002 using a GeoExplorer Model 3 Global Positioning System (GPS) unit and GPS Pathfinder Office 2.70 software (Trimble Navigation Limited, Sunnyvale, CA). These areas were then overlaid in ArcView GIS 3.2 against existing treatment unit maps, and size was determined for each beetle infestation (Environmental Systems Research Institute, Inc., Redlands, CA).

SPB Trapping

Collection of beetle specimens began in May of 2001 and ended in October of 2001. A total of 20 flight-intercept traps (Hines and Heikkenen 1977) was placed in each of the 4 treatment units of a single replication for a 7-day period. In each treatment unit, five grid points were randomly chosen for trap location. Following the 7-day trap period, traps were removed from the four treatment units of that replication to the four treatment units of the next replicate.

Each trap was constructed from two pieces of 30- by 40-cm medium-grade Plexiglas and a 30-cm diameter plastic funnel. Using a band saw, a 20-cm slit was cut into the long side of each of the pieces of Plexiglas. The two pieces were then connected at the slits and held together with epoxy glue. Four 2.5-cm slits, each at 90° angles from one another, were cut into the top of the rim of the plastic funnel using a band saw. The connected pieces of Plexiglas were fitted and glued into these slits. Two small holes were drilled at the top of each of the two pieces of Plexiglas.

A 25-pound test fishing line was tied to a metal weight and tossed over a live, thick pine branch. The end of the line was then tied through the holes at the top of the flight-intercept trap. A 125-ml plastic jar with a 3-cm-wide mouth was half-filled with water and a drop of laundry detergent. The jar was fitted against the stem of the funnel, and the trap was hoisted in the air until it reached a height that represented the average mid-bole height of the pines surrounding the particular grid point. The trap was brought down after a week of sampling. Contents of the plastic jar were examined in the laboratory, and only beetle specimens from Scolytidae were counted and identified to species.

Oleoresin Flow

Oleoresin flow was measured during July 2001 on four randomly selected pines at the same five grid points per treatment unit that flight-intercept traps were placed. Using a 2.54-cm arc punch, one north-facing core and one south-facing core were drilled into the bole of the sampled tree at breast height. A piece of aluminum flashing was constructed into the shape of a funnel and placed below each of the circular tree cores. A pre-weighed 15-ml plastic centrifuge tube was placed below the flashing. After a 24-hour period of collecting resin, each tube was weighed to determine the relative amount of resin flow in each pine (McCall 2000).

Latewood Percentage

Increment cores were removed during the winter of 2002 from the same four pines at each grid point that had been sampled for oleoresin flow. Cores were placed in mounting blocks constructed from shelving. The length of earlywood and latewood bands from the past year and the past 5 years was measured using a Bannister incremental measuring machine (Jacobi 1987).

Statistical Analysis

The number of SPB caught in each treatment unit throughout the 6-month trapping period was used as an index of stand-level beetle incidence. Infestation size per treatment

unit was also used as an index of incidence. Averages of infestation size and total trap catch were used to determine the level of SPB incidence across a treatment type. Mean 24-hour resin weight per pine and recent 5-year latewood percentage were used to determine the level of host resistance across treatment units. Analysis of variance was used to determine treatment differences on both SPB incidence and host resistance. Regression analysis was used to determine correlations between host resistance and SPB incidence across a stand level.

RESULTS AND DISCUSSION

SPB Response to Treatments

During the sampling period, populations of SPB throughout the Piedmont of South Carolina reached epidemic levels. A total of 210 SPB was caught in flight-intercept traps throughout the 6-month trapping period (fig. 1). Post-treatment 2001 SPB infestations were found on all but 1 of the 12 treatment units (table 1). Initial examination of infestation size and trap-catch data indicated that both prescribed burning and thinning had no effect on short-term incidence of SPB (table 2). The non-homogenous variance in these data could be explained by the presence or absence of a flight-intercept trap in the path of an active SPB spot head. If a trap was not up when an active spot head moved through a grid point, then trap catch numbers were much lower than if the trap had been up when the spot moved through. This may help to explain why trap catch numbers were so disparate between treatment units that had large SPB infestation sizes—Replication 1 Control, Replication Thin A, Replication 2 Burn, and Replication 3 Thin B.

Coster and Searcy (1981) reported that site factors, rather than stand condition, were related to the occurrence of infestations of SPB in the Piedmont. These site factors include percentage of clay in the soil surface, slope percentage, and specific tree density. Silvicultural treatments such as prescribed burning and thinning may reduce a stand's susceptibility to a beetle attack. However, if site factors are present that increase the likelihood of an attack, then these treatments could possibly play no part in reducing stand susceptibility. Furthermore, burning and thinning actually can cause short-term increases of SPB due to short-term tree stress. However, burning and thinning can reduce overall beetle incidence by reducing pine density (Hedden and Billings 1979).

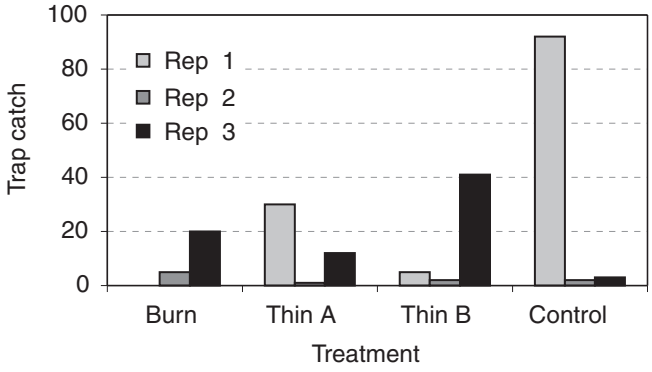

Figure 1—Number of SPB caught in flight-intercept traps from May through October 2001.

Table 1—Area of SPB infestations in each of the 12 treatment units

Replication	Treatment	2001 infestation size
		ha
1	Burn	0.29
2	Burn	3.31
3	Burn	1.31
1	Thin A	4.81
2	Thin A	0.49
3	Thin A	0.22
1	Thin B	0.00
2	Thin B	0.14
3	Thin B	1.26
1	Control	4.24
2	Control	0.78
3	Control	0.38

Table 2—Mean response of Southern Pine Beetle incidence and host vigor characteristics to treatments

Treatment	Trap catch	2001 infestation size	24-hour resin weight	Recent 5-year latewood percentage
		ha	*g*	
Burn	8.3a ± 6.0	1.64a ± 0.89	9.15a ± 2.16	43.80a ± 1.35
Thin A	14.3a ± 8.5	1.84a ± 1.49	10.33a ± 3.01	43.67a ± 2.28
Thin B	16.0a ± 12.5	0.47a ± 0.40	9.18a ± 0.83	46.14a ± 1.73
Control	32.3a ± 29.8	1.80a ± 1.23	8.05a ± 2.17	45.34a ± 3.41

Means ± standard error followed by same letter in each column are not significantly different at the $P < 0.05$ probability level

Host Vigor Characteristics and SPB Activity

July oleoresin flow and latewood percentages were not affected by any of the treatments (table 2). There were, however, stand level interactions between SPB activity, resin flow, and recent 5-year latewood percentages. We observed significant relationships between both trap catch (fig. 2), (p = 0.04)) and the size of 2001 SPB infestations (fig. 3), (p = 0.003) with the log of 24-hour resin weight. This pattern suggests that as total resin flow across a treatment unit increased, beetle activity within that stand decreased. The three treatment units with the largest beetle infestations in year 2001—Replication 1 Control, Replication 1 Thin A, and Replication 2 Burn—had the lowest total resin weight of all treatment units. These results are consistent with the previous understanding that the oleoresin system of pines is the primary defensive mechanism against attacking SPB (Lorio and others 1995).

There was a stand level positive relationship between 24-hour resin flow and recent 5-year latewood percentages (fig. 4), (p = 0.007). The data presented here suggest that the relative amount of latewood a tree establishes has effects on the amount of resin flow that is produced. Latewood percent in mature pines may be a good indicator of resistance to SPB attack. Strom and others (2002) recently showed that progeny of pines, which escaped or survived SPB attack when surrounding pines were killed, had significantly greater resin flow when compared to the progeny of randomly sampled, unattacked pines from the same area. Latewood percent and resin-duct density are just two of several factors controlling oleoresin flow. Other factors include the moisture status of the tree and the amount of photosynthate produced. Photosynthate production is closely related to the crown percent and total leaf area of the pine (Dunn and Lorio 1992). Pines with large crowns will have greater oleoresin flow than trees of the same age with small crowns.

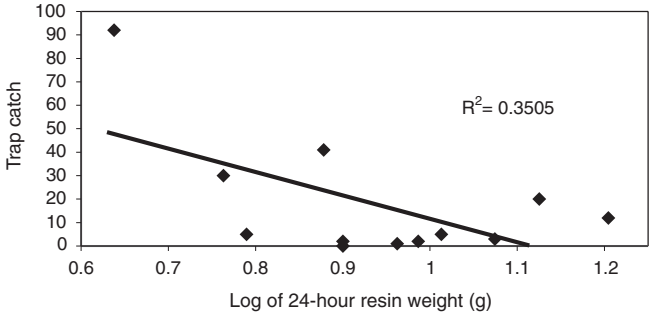

Figure 2—Relationship between the total number of SPB caught and a logarithmic transformation of mean 24-hour resin weight within each treatment unit (n = 12).

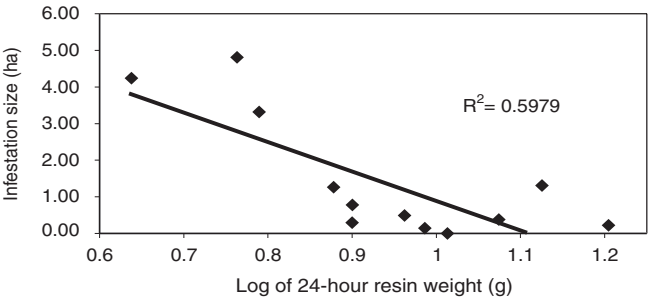

Figure 3—Relationship between the SPB infestation size and a logarithmic transformation of mean 24-hour resin weight within each treatment unit (n = 12).

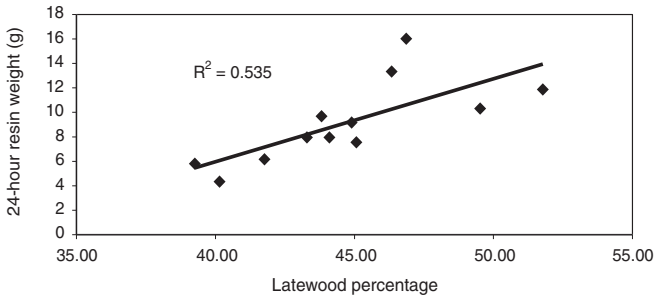

Figure 4—Relationship between mean 24-hour resin weight and mean recent 5-year latewood percentage within each treatment unit (n = 12).

Changing environmental conditions such as drought can also substantially affect the percentage of latewood in the annual ring (Zahner 1962). During periods of drought, the transition of latewood occurs earlier than in wetter years (Lorio and others 1990). Northwest South Carolina was undergoing a period of severe drought during this study. We speculate that the severe drought accentuated differences in latewood percentage, and, consequently, the vertical resin duct density in trees between sites. These differences apparently had a significant effect on stand level resistance to SPB mortality.

Even though there were no significant short-term effects of thinning and fire on SPB mortality in this study, the long-term effects could be pronounced. Thinning, and possibly burning, will reduce intra-tree competition, therefore providing for an increase in leaf area, which should result in a greater supply of photosynthate available for oleoresin production. Response of latewood production following thinning and fire will probably be site specific (Megraw 1985). Where moisture is limiting, increased water status can lead to a significantly greater percentage of latewood (Megraw 1985, Zahner 1962). However, in general, the absolute amount of latewood produced will be directly related to the growth rate of the tree whereas the percentage of latewood will be unaffected (Zobel 1995). Because the resin duct system of the pine is the site of oleoresin production, increased amounts of latewood—everything else being equal—will result in greater oleoresin flow and reduced mortality due to SPB attack.

CONCLUSIONS

Total 24-hour resin flow had a significant positive correlation with recent 5-year latewood percentages across treatment units. Also, resin flow was inversely related to beetle activity. These data provide further evidence to the hypothesis that resin flow is the primary host defense mechanism against invading SPB. Furthermore, the

amount of recent latewood formed may be a critical factor in the determination of total amount of resin flow produced by the host conifer.

Fire and thinning had no short-term effects on SPB incidence of attack or host resistance mechanisms. It is yet to be determined what long-term effects fire and thinning have on SPB spot occurrence and growth in the Piedmont. However, reduction in stand density along with increased tree vigor should result in lower long-term susceptibility to SPB attack.

ACKNOWLEDGMENTS

This is Contribution Number 28 of the National Fire and Fire Surrogate Project (NFSS), funded by the U.S. Joint Fire Science Program.

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FIRE MONITORING: EFFECTS OF SCORCH IN LOUISIANA'S PINE FORESTS

James D. Haywood, Mary Anne Sword, and Finis L. Harris[1]

Abstract—Frequent growing-season burning is essential for restoring longleaf pine (*Pinus palustris* Mill.) plant communities to open parklike landscapes. However, fire can be a destructive force, reducing productivity and causing mortality among overstory longleaf pine trees. On two central Louisiana sites, severe crown scorch reduced longleaf pine diameter growth by 22 percent during five growing seasons after prescribed burning. Crown scorch also reduced root sucrose and starch concentrations, total and live fine-root-mass density, and the initiation of secondary root development. Despite these results, restoring and maintaining historic plant communities as habitat for endangered species is worth a moderate reduction in growth and some root injury among overstory longleaf pine trees.

INTRODUCTION

Restoring longleaf pine (*Pinus palustris* Mill.) plant communities in the Southern United States can provide desirable habitat for nearly 200 threatened or endangered taxa of vascular plants and several vertebrate species (Brockway and others 1998). Frequent growing-season burning is essential for restoring these plant communities, and mature longleaf pine ecosystems require recurrent burning at 2- to 4-year intervals to maintain species-rich understories of native herbaceous plants (Haywood and Harris 1999).

However, fire may reduce productivity and kill overstory longleaf pine trees (Boyer 1987, Boyer and Miller 1994). The decreases in longleaf pine growth on routinely burned sites may be linked to the intensity and timing of burning relative to the seasonal pattern of carbon allocation in trees. Fire-exposed foliage is an important carbon source, and its vulnerability to heat injury may affect stand productivity. We studied how crown scorch influenced the availability of carbohydrates for longleaf pine root metabolism and growth over a 1-year period after burning; we also studied the amount of stem growth over five growing seasons after burning.

METHODS

The study trees are located in two stands on the Kisatchie National Forest, Calcasieu Ranger District, Rapides Parish, LA. In September 1996, at site 1, a stand of 65-year-old longleaf pine was prescribed burned using a series of strip head fires. At strip interfaces, the crowns of longleaf pine were nearly defoliated by late fall. Along 2 of these interfaces, 10 defoliated trees were selected, as were 10 adjacent nonscorched longleaf pine trees. Thus, 40 (20 scorched and 20 nonscorched) trees were studied.

At site 2 in March 1997, a stand of predominately 45-year-old slash pine (*P. elliottii* Engelm.) was prescribed burned using a helicopter-mounted ignition system. Most of the slash pine was scorched. However, there were also natural longleaf pines in the overstory (these trees were > 45 years old), and 10 of the nonscorched longleaf pines were paired with adjacent scorched longleaf trees in May 1997. In total, 20 longleaf pines were studied (10 nonscorched and 10 scorched) within this predominately slash pine stand.

Soils at site 1 were Ruston fine sandy loam on the ridges and Smithdale fine sandy loam on the side slopes. At site 2, the soil was predominately Beauregard silt loam. At both sites in May 1997 and September 2001, tree diameter at breast height (d.b.h.) was measured with a diameter tape and total height with a Criterion 400 Survey Laser (Laser Technology, Inc., Englewood, CO). At site 1 in May 1997 through April 1998, one soil core was randomly collected monthly to a 20-cm depth within 2 m of each tree (Sword and Haywood 1999). Roots were washed from the soil cores and cleaned. Fine-root carbohydrate concentrations and biomass were determined.

For the longleaf pine trees, the dominant effect in this study was crown scorch; thus, we compared d.b.h. and total height using a completely randomized analysis of covariance design with the May 1997 measurements as covariates (Steel and Torrie 1980). At site 1, root data were transformed to natural logarithms and evaluated by a randomized complete block analysis of variance design. Blocking was based on topography.

RESULTS

Longleaf pine d.b.h. growth was significantly less for the scorched trees than for the nonscorched trees during five growing seasons after prescribed burning (1997 to 2001) (table 1). Total tree height, however, was not similarly affected.

Longleaf pine root sucrose and starch concentrations varied seasonally, but overall they were significantly reduced in response to crown scorch through February 1998 (Sword and Haywood 1999) (fig. 1). One year after burning, total and live pine fine-root-mass densities were significantly lower in response to crown scorch (fig. 2). However, this effect was not evident at earlier sampling dates. Also, 1 year after burning, the percentage of live roots exhibiting primary growth was significantly greater for the

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Table 1—Comparisons of longleaf pine d.b.h. and total height over a 5-year period between nonscorched and scorched trees[a]

Groupings	May 1997	Sept. 2001	*P*-value
	- - d.b.h. (cm) - -		
Nonscorched	40.9	43.2	0.0089
Scorched	39.1	40.8	
	Total height (m)		
Nonscorched	25.1	25.8	0.2386
Scorched	24.4	25.0	

D.b.h. = diameter at breast height.
[a] The May 1997 data were used as covariates in the analysis of covariance.

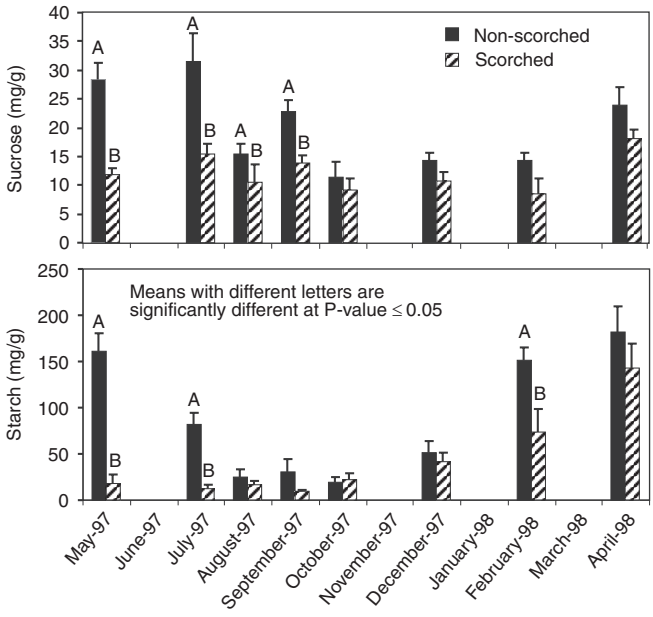

Figure 1—Longleaf pine fine-root sucrose and starch concentrations 8 to 15 months after crown scorch occurred in September 1996.

scorched pine trees, but more importantly, secondary root mass was reduced in response to crown scorch.

DISCUSSION AND CONCLUSIONS

Severe crown scorch reduced diameter growth by 22 percent during five growing seasons after prescribed burning (table 1). Total height, however, was not significantly affected. During the prolonged drought of 1998 through 2000 in Central Louisiana, water deficits likely inhibited the growth of the nonscorched trees. However, the growth of the scorched trees was most inhibited by the loss of nearly 100 percent of foliage in fall 1996 and the need to replace this foliage. Therefore, without drought influencing the growth of the nonscorched trees, we expect that diameter growth reductions after crown scorch would have been more

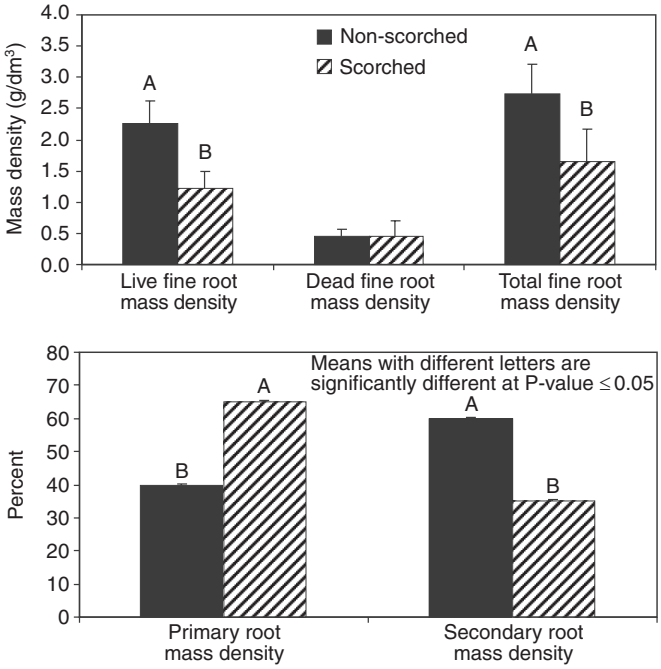

Figure 2—Longleaf pine fine-root-mass density (top) and percentage of root mass exhibiting primary and secondary development (bottom) in September 1997 and 1 year after crown scorch occurred.

pronounced and total height growth differences may have been apparent.

Crown scorch also reduced root sucrose and starch concentrations, total and live fine-root-mass density, and the initiation of secondary root development. Fire-induced loss of leaf area potentially reduces carbon fixation and allocation to the stem and root system. However, the magnitude and duration of these effects depend on the amount and season of leaf-area loss, as well as interacting site quality and climate factors.

Nevertheless, the need to restore and maintain historic forest types as habitat for endangered species is worth a moderate reduction in growth among large overstory longleaf pine trees. Regular prescribed burns will reduce fuel loading and favor development of grass-dominated understory vegetation. These fine fuels should support fast-moving fires and eventually reduce the potential for crown scorch following future burns.

FUTURE RESEARCH

In a long-term study, we continue to investigate the effects of prescribed fire on longleaf pine root and stem development. Our work is now concentrated in new longleaf pine plantations on upland sites being converted from hardwood and loblolly pine (*P. taeda* L.) to the historic longleaf pine landscape. We hope to determine how fascicle physiology, leaf-area dynamics, growth, and carbon allocation of sapling longleaf pine are affected by fuel treatments that yield varied fire intensities. At the same time, we evaluate long-term effects of prescribed burning on soil chemical and physical properties.

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LONG-TERM EFFECTS OF SEASON OF PRESCRIBED BURN ON THE FINE-ROOT GROWTH, ROOT CARBOHYDRATES, AND FOLIAR DYNAMICS OF MATURE LONGLEAF PINE

Eric A. Kuehler, Mary Anne Sword-Sayer, James D. Haywood, and C. Dan Andries[1]

Abstract—Depending on the season and intensity of fire, as well as the phenology of foliage and new root growth, fire may damage foliage, and subsequently decrease whole-crown carbon fixation and allocation to the root system. In central Louisiana the authors investigated how season of prescribed burning affects fine-root dynamics, root carbohydrate relations, and leaf area production in 45-year-old longleaf pine. After achieving a steady state, fine-root production was greater in plots burned in March and May than in those burned in July. In both 1998 and 2000, root starch metabolism was lower on plots burned in July than on those burned in May. Month of biennial prescribed fire did not appear to affect leaf area production. However, foliar magnesium concentration was greater in plots burned in March and May than in those burned in July. These results indicate that additional mechanisms of reduced root growth in response to repeated burning are possible. The authors speculate that on this study site, season of prescribed burn influenced root growth by affecting mineral nutrition and root carbohydrate metabolism.

INTRODUCTION

The acquisition of water and mineral nutrients by roots is required for sustained forest growth. Root growth and function depend on carbon fixation in the crown and allocation to the root system. Fire damage to the crown of longleaf pine (*Pinus palustris* Mill.) may reduce the amount of carbon available to the root system (Johansen and Wade 1987, Sword and Haywood 1999). Furthermore, the risk of fire-induced damage to the crown increases as foliage production and drought potential increase during the growing season. Thus, the potential impact of repeated prescribed fire on root growth and function may vary by season. The objective of this study was to determine if longleaf pine fine-root production and carbohydrate concentrations respond differently to repeated prescribed fire in March, May, and July.

MATERIALS AND METHODS

The research area is located in a 45-year-old longleaf pine stand on the Palustris Experimental Forest in the Kisatchie National Forest, Rapides Parish, LA. The study site is described in Haywood and others (2001). Measurements were conducted in three- to four- and six- to seven-tree clusters in two replications of three prescribed-burning treatments (March, May, or July biennial burns) in a completely randomized design. Biennial prescribed burning treatments were applied as strip head fires beginning in 1966, with the latest in 1998. Volume and basal area of the clusters were not affected by the month of prescribed burning.

Leaf area index was monitored monthly using two LI-COR LAI-2000 Plant Canopy Analyzers (LI-COR, Inc., Lincoln, NE) from March 1998 to April 2001. The monthly readings were taken along permanent transects in each six- to seven-tree cluster and in a nearby open field for comparative purposes. Fine-root quantity and biomass on an ash-free basis were determined using 785-cm^3 in-growth cores (Vogt and Persson 1991) installed on a 0.3-m^2 grid within 5 m of trees in six- to seven-tree clusters. The cores were installed in February 1998. Six in-growth cores were extracted from all plots every 2 months between August 1998 and February 2000. Root carbohydrate concentration was measured monthly in three- to four-tree clusters. Five soil cores were extracted from random locations in the periphery of the clusters. Roots (2 to 5 mm in diameter) from the cores were pooled, washed, freeze dried, and ground to pass through a 20-mesh screen. Concentrations of root starch, sucrose, and glucose were determined enzymatically (Jones and others 1977). Foliar samples from the upper crown of three trees per plot were collected in January 2001. A LECO CNS-2000 elemental analyzer was used to determine foliar nitrogen (N) concentration. Foliar phosphorus (P) concentration was determined colorimetrically (John 1970), and foliar potassium (K), calcium (Ca), and magnesium (Mg) concentrations were determined by atomic absorption (Isaac and Kerber 1971). Treatment differences in fine-root quantity and biomass, root carbohydrate concentrations, and foliar nutrients were statistically tested using analysis of variance procedures.

RESULTS AND DISCUSSION

Month of biennial prescribed fire did not affect leaf area production. Prolonged drought during the 1998 to 2000 study period (Haywood and others, in press) may have reduced leaf area production and interfered with the seasonal pattern of foliage senescence. As a result, prolonged drought may have interfered with potential leaf area responses to prescribed burning treatments. After achieving a steady state of root production 14 months after in-growth core installation, month of prescribed burn significantly affected total (live plus dead) fine-root quantity [probability of a greater F-value (P) = 0.0536] and live fine-root quantity (P = 0.0392) (fig. 1A). Similarly, live fine-root

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

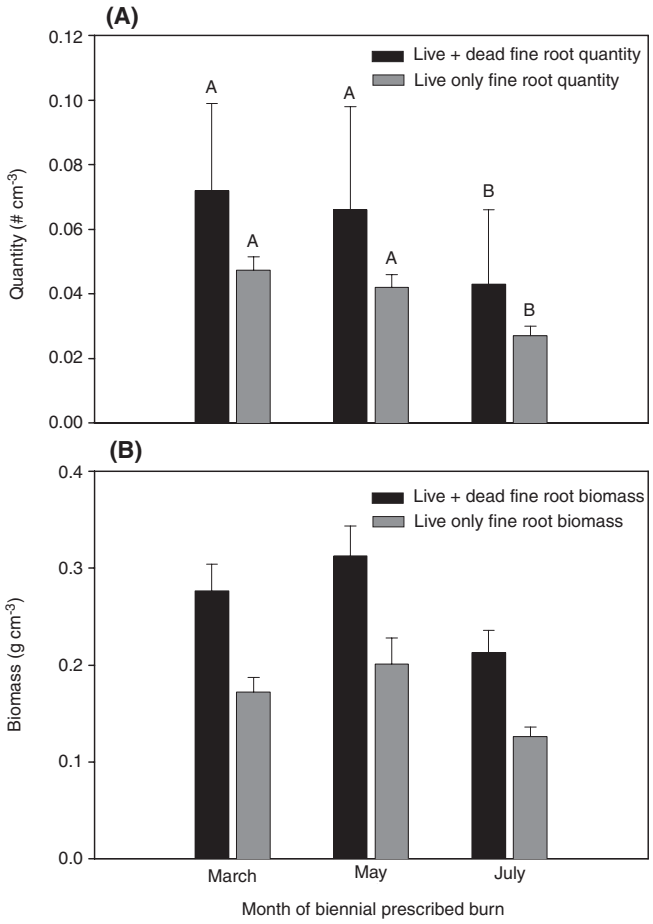

Figure 1—Mean total (live plus dead) and live-only longleaf pine fine-root quantity (number/cm^3) (A) and biomass (g/cm^3) (B) between April 1999 and February 2000 in response to month of biennial prescribed burn. Means associated with a different letter are significantly different at a *P* d" 0.10 by least squares means.

biomass was differentially impacted by sampling date and month of prescribed burn (*P* = 0.0345). In April 1999, May-burn root biomass was significantly greater than March- and July-burn biomass; however, in December 1999, the May-burn biomass was only significantly greater than the July-burn biomass (fig. 1B). These main and interaction effects indicate that fine-root production was lower on plots that were prescribed burned in July than on those that were prescribed burned in March or May.

Root starch and glucose concentrations varied seasonally. A reduction in annual peak starch (21 percent in 1999 and 2000 compared with 1998) and glucose (28 percent in 2000 compared with 1998 and 1999) was observed. Mean annual root sucrose concentration increased 125 percent in 2000 compared with 1998 and 1999. Root starch concentrations were significantly different by sampling date and month of prescribed burn (*P* = 0.0807). Specifically, the rate of starch depletion from roots between May and October was lower on the July-burned plots than on the May-burned plots in 1998 and 2000 (fig. 2).

Foliar nutrient concentrations indicated that P was deficient, N and Ca were nearly deficient, and Mg and K were sufficient in all treatments as defined by Blevins and others (1996). Foliar Mg concentration was significantly lower (*P* = 0.0100) on the July-burned plots than on the March- and May-burned plots (table 1).

These results demonstrate consistent effects of season of prescribed fire on fine-root production, root starch metabo-

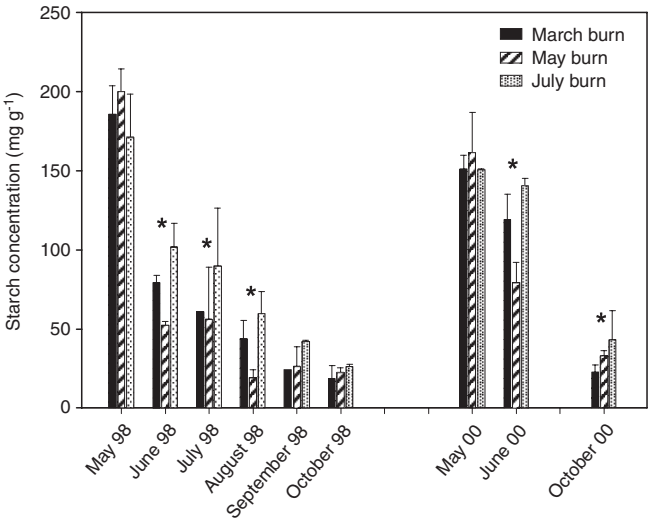

Figure 2—Longleaf pine root starch concentration (mg/g) between May and October of 1998 and 2000 in response to month of biennial prescribed burn. An asterisk (*) above the group of bars indicates statistical significance between May- and July-burn treatments at a *P* d" 0.05 by least squares means. Data from November 1998 to April 2000 are not shown. Between July and September 2000, root samples were not collected.

Table 1—Dormant season mean longleaf pine foliar nutrient levels (± 1 standard error) in response to month of biennial prescribed burn

		Month of biennial prescribed burn		
Nutrient	Critical level[a]	March	May	July
N (*percent*)	0.95	1.02 (0.09)	0.97 (0.03)	0.92 (0.03)
P (*g kg^{-1}*)	0.80	0.71 (0.06)	0.70 (0.05)	0.70 (0.04)
K (*g kg^{-1}*)	3.00	3.61 (0.17)	3.20 (0.17)	3.19 (0.40)
Ca (*g kg^{-1}*)	1.00	0.95 (0.10)	0.94 (0.04)	1.13 (0.13)
Mg (*g kg^{-1}*)	0.60	0.97 (0.06)a[b]	1.07 (0.05)a	0.78 (0.07)b

[a] Concentration below which the nutrient is considered deficient (Blevens and others 1996).
[b] Means followed by different letters are significantly different at a probability less than or equal to 0.05 by Least Squares Means.

lism, and foliar Mg concentration. Because leaf area production was unaffected by season of prescribed fire in this study, conclusions about how seasonal fire regimes affect leaf area production and carbon allocation to fine-root production cannot be made. Prolonged drought may have distorted root carbohydrate relations by increasing the sucrose concentration (in 2000) and decreasing peak glucose (in 2000) and starch (in 1999 and 2000) concentrations. A similar interference may have occurred with leaf area and fine-root production and with foliar nutrition. Continued research is warranted to understand the long-term effect of season of repeated prescribed fire on fine-root production.

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EFFECTIVENESS OF FIRE AND FIRE SURROGATE TREATMENTS FOR CONTROLLING WILDFIRE BEHAVIOR IN PIEDMONT FORESTS: A SIMULATION STUDY

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Abstract—The need for fuel reduction has increased in United States forests due to decades of fire exclusion. Excessive fuel buildup has led to uncharacteristically severe fires in areas with historically short-interval, low-to-moderate-intensity fire regimes. The National Fire and Fire Surrogate (NFFS) Study compared the impacts of three fuel-reduction treatments on numerous response variables. At an NFFS Study research site in the South Carolina Piedmont, fuels were altered by burning, thinning, and the combination of burning and thinning. Each treatment produced a unique fuel complex and altered microclimate for surface fuels by opening stands to wind and light. Fuel-reduction treatments were designed to minimize damage if a wildfire occurred; however, fire behavior in each treatment area is difficult to predict. BehavePlus was used to predict wildfire behavior for treatment comparisons. Fuel and weather data collected from each treatment area were used as inputs to simulate wildfire behavior for extreme weather conditions during the Piedmont fire season. Burn-only treatments had the shortest flame heights, slowest rate of spread, and lowest scorch height. Thin-only and thin-and-burn treatments increased fire intensity for the first growing season after treatment. However, these results are expected to be short term as logging slash decomposes.

INTRODUCTION

Excessive amounts of fuel have accumulated in many forests throughout the United States due to fire suppression over the past few decades. Annually South Carolina suppresses about 5,000 to 6,000 wildfires that burn a total of 30,000 acres.

Two western studies of fuel-treatment effects on wildfire behavior by van Wagtendonk (1996) and Stephens (1998) found that prescribed fire reduced severe fire behavior more than thinning. Stephens also found that thinning followed by prescribed burning would not produce extreme fire behavior at 95th-percentile weather conditions. Van Wagtendonk suggested that managing forests with a combination of fuel treatments is critical in reducing the size and intensities of wildfires.

In a similar study, Brose and Wade (2002) found that prescribed fire was the most effective treatment for immediate fuel reduction. Thinning was less effective than prescribed burning, but more effective than herbicide due to disruption of fuel continuity. Herbicide treatments resulted in no decrease in fire behavior for the first year, but showed a dramatic decrease in fire behavior in the second year. Brose and Wade suggested combining treatments for the most effective reduction of hazardous fuels and maintaining ecosystem health. A study in Portugal by Fernandes and others (1999) found that fuel treatments consisting of any physical fuel elimination, such as prescribed burning and mechanical treatment with slash disposal, were effective short-term solutions for reducing wildfire behavior.

Fuel-reduction treatments at the Piedmont site followed National Fire and Fire Surrogate (NFFS) Study protocols and included three replications of four treatments: control, prescribed burning, thinning, and the combination of thin-and-burn. Treatments altered the fuel complex and microsite climate differently, which could produce different wildfire intensities and severities. Using measured fuel data from the treatments and extreme fire weather as variables in the model, we estimated wildfire behavior to determine if fuel-reduction treatments adequately protect forests from wildfire.

NFFS Study

This national study compares ecological and economic impacts of fuel-reduction treatments. The study consists of 13 sites across the United States where fire has played an historical role. These areas currently have excessive fuel buildup and are considered to be at risk of wildfire. Eight sites are located in the Western United States, with the remainder in the Eastern United States. Each site follows the same protocols for treatments and data collection to allow for a national database of core variables.

Location

The Piedmont NFFS study is located on the Clemson Experimental Forest in northwest South Carolina. The research sites are in second- or third-growth timber with loblolly pine *(Pinus taeda* L.) and shortleaf pine (*P. echinata* Mill.) as the dominant species. The fire-return interval ranges from 1 to 30 years.

METHODS

The Piedmont NFFS Study site consists of three replications of four treatments. Treatments used were burn-only, thin-only, thin-and-burn, and control. Within each treatment 40 grid points were established on 50- by 50-m spacing. At each grid point, fuel data were collected on three fuel transects using the Brown's Planar Intersect Method (Brown

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

1974). One-, ten-, and one hundred-hour fuels were inventoried, and fuel height was measured on each transect. Data were used to develop custom fuel models in the BehavePlus fire modeling system (Andrew and others 2002).

RainWise, Inc., WS2000 weather stations were placed in a central location within each treatment area for 2 weeks to compare treatment microsite differences. Each WS2000 weather station collected temperature, relative humidity, windspeed, wind direction, and rainfall at 10-minute intervals. Four additional RainWise, Inc., MK3 weather stations were located in open fields on the Clemson Forest for a total of 6 weeks. These units collected temperature, relative humidity, windspeed, and wind direction at 10-minute intervals. The 12 treatment areas also had a HOBO® weather recorder that logged temperature and relative humidity for 5 weeks. Weather data were downloaded weekly.

Regression equations were developed to predict stand weather conditions based on weather reported in open areas. These equations estimated the high temperature, low relative humidity, and high midflame windspeed that would occur in each treatment on an 80th-percentile day during the fire season. Using estimated weather variables, BehavePlus simulated fire behavior in each treatment.

RESULTS

Fuel Loads

Thin-only treatments increased 1-, 10-, and 100-hour fuels, with 100-hour fuels increasing the most (fig. 1). Burn-only reduced 1- and 10-hour fuels more than 100-hour fuels. Thin-plus-burn reduced 1-hour fuels, but 10- and 100-hour fuels increased.

Weather Conditions

Ambient temperatures were lowest in thin-only treatment areas and highest in thin-plus-burn areas (fig. 2). Relative humidity was lowest in control treatments and highest in thin-only treatments (fig. 3). Highest midflame windspeeds were recorded in burn-only and thin-plus-burn areas; both were approximately 7 miles per hour (fig. 4). Control and thin-only treatments had midflame windspeeds averaging 4 miles per hour. Prescribed burning reduced cover of understory trees and shrubs; therefore, winds in burn-only and thin-and-burn treatments were higher.

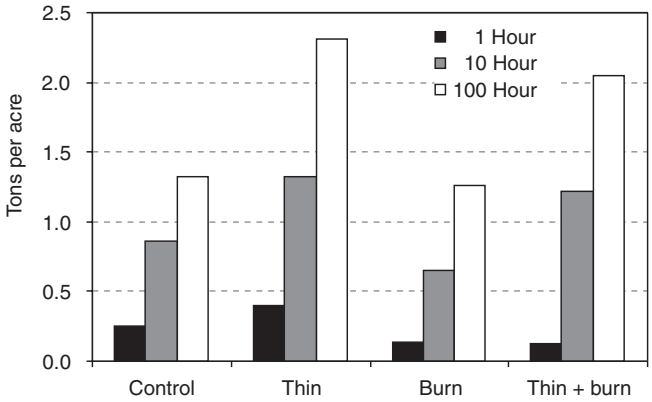

Figure 1—Average fine woody fuels in tons per acre on all treatments posttreatment.

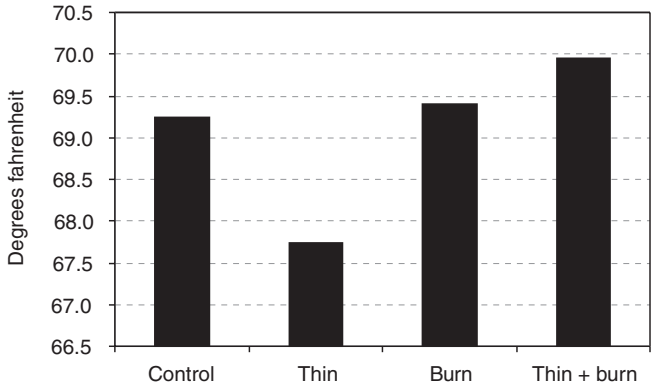

Figure 2—Maximum ambient temperature in degrees Fahrenheit posttreatment.

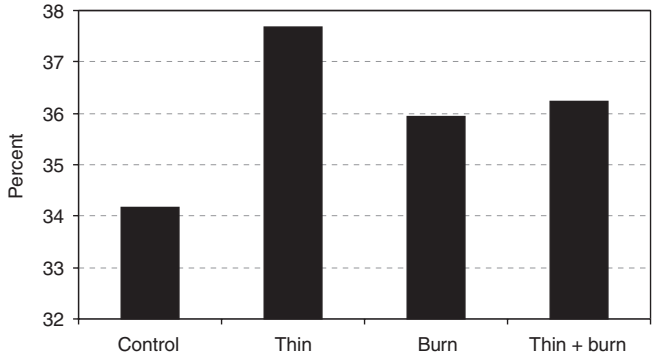

Figure 3—Lowest percent relative humidity posttreatment.

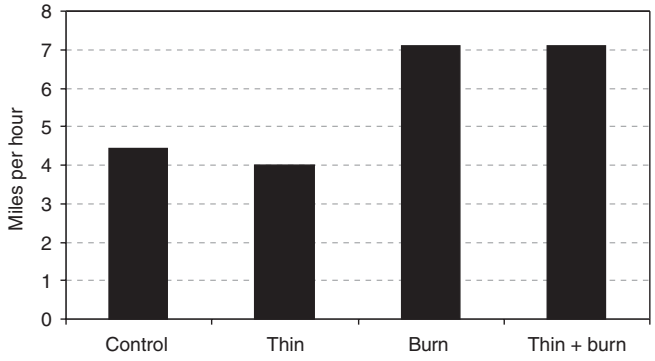

Figure 4—Maximum windspeed in miles per hour posttreatment.

Wildfire Behavior

BehavePlus (Andrews and others 2002) predicted that wildfire flame lengths would be tallest in thin-and-burn and thin-only treatments where 10- and 100-hour fuel loads were high (fig. 5). Rate of spread was slowest in burn-only areas where most 1- and 10-hour fuels had already been consumed (fig. 6). Scorch height was lowest in burn-only areas, again due to reduced fuels (fig. 7).

CONCLUSIONS

The BehavePlus model suggests that prescribed burning as a fuel-reduction treatment is an effective method for reducing wildfire damage in the Piedmont. Burning must occur periodically over the long term to maintain low fuel loads, thereby decreasing the chance of wildfire. Thin-and-

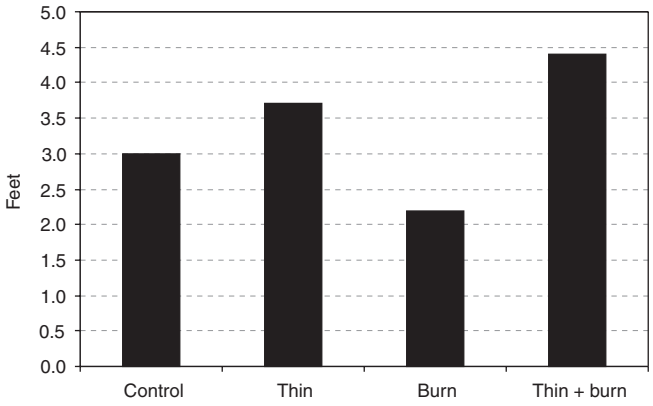

Figure 5—Maximum simulated flame length posttreatment in feet by BehavePlus.

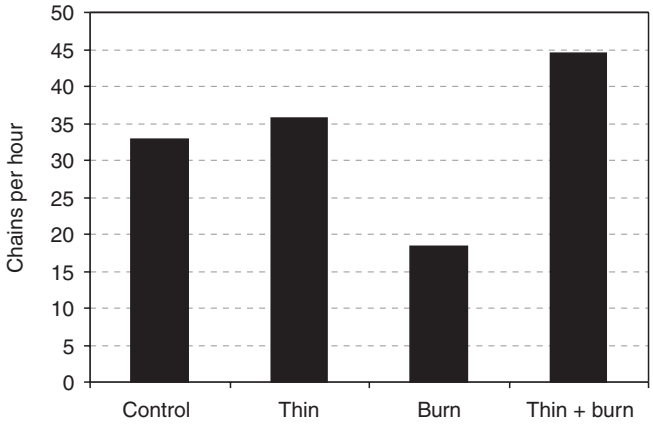

Figure 6—Maximum simulated rate of spread posttreatment in chains per hour by BehavePlus.

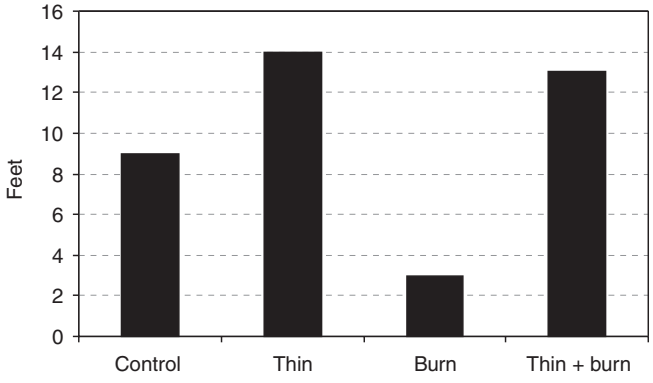

Figure 7—Maximum simulated scorch height in feet posttreatment by BehavePlus.

burn treatments may also decrease fuels if burning is repeated periodically over the long term. Continued data collection and treatments on the NFFS Study allow us to more clearly see the ecological impacts of repeated treatments.

ACKNOWLEDGMENTS

This is Contribution Number 29 of the NFFS Project, funded by the U.S. Joint Fire Science Program.

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EFFECTS OF VEGETATION MANAGEMENT WITH PRESCRIBED FIRE ON SOIL PHYSICAL PROPERTIES IN A YOUNG LONGLEAF PINE STAND

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Abstract—The intensity and frequency of prescribed fire affects soil properties that control its quality. This project evaluates how six vegetation management treatments, four of which include biennial prescribed fire, affect the soil physical properties in two stands of longleaf pine (*Pinus palustris* Mill.) located on the Kisatchie National Forest, Rapides Parish, LA. The A, Bt1, and Bt2 horizons were evaluated 1 year after the initial prescribed burn. Differences in soil properties between the two stands were apparent in all three horizons. The application of treatments that included the chemical control of woody competition resulted in higher bulk density and lower total porosity of the Bt1 horizon. As long-term biennial prescribed fire continues to remove litter and control woody competition, bulk density and total porosity may respond similarly.

INTRODUCTION

Repeated prescribed fire every 2 to 10 years is essential to perpetuate longleaf pine (*Pinus palustris* Mill.) ecosystems (Outcalt 1997) and is a valuable stand-management tool in the Southeast. The frequency and intensity of prescribed fire affects stand and soil variables that control whole-crown carbon fixation, root system expansion, and therefore, tree growth and water and mineral nutrient uptake. Because pre-fire fuel conditions, in part, control the intensity of prescribed fire, it is of interest to investigate long-term responses of soil properties to vegetation management treatments that affect fuel conditions. This information will help to identify fuel conditions and vegetation management treatments that minimize negative effects of fire on soil properties.

The effects of repeated prescribed fire on forest productivity have generated controversy. Research by Boyer (1987) indicated a reduction in tree growth. However, Waldrop and others (1987) reported inconclusive effects of repeated prescribed fire on tree growth, and Brockway and Lewis (1997) showed no negative effect of routine prescribed fire on southern pine productivity.

Reductions in forest productivity resulting from repeated prescribed fire could be attributed to the effects of crown scorch and leaf area loss on whole-crown carbon fixation and allocation (Johansen and Wade 1987, Sword and Haywood 1999). This could lead to reductions in carbon allocation to root growth and, thus, soil resource uptake. Although frequent prescribed fires usually increase the organic matter content of the surface soil (Lotti 1962, Metz and others 1961, Neary and others 1999), fire-induced reduction in root growth may cause decreases in subsoil organic matter over time. This could result in a decrease in soil water holding capacity and an increase in soil strength and bulk density (Fisher and Binkley 2000).

A second mechanism of reduced forest productivity with repeated prescribed fire is a cumulative loss of soil quality. Again, however, the occurrence of negative effects of fire on soil properties is variable. In mature longleaf pine, Boyer and Miller (1994) found that biennial winter burning reduced soil macropore space and plant-available water, and increased soil bulk density. Moehring and others (1966) found that biennial prescribed burning increased soil bulk density and decreased soil macroporosity, but these responses were apparent only in the upper 5 cm of mineral soil. Minor increases in bulk density were found by Bower (1966) in response to fire, but this effect dissipated within 4 years after treatment. Lotti (1962) and Metz and others (1961) found that the type or frequency of prescribed fire had no detrimental effect on the bulk density or porosity of loblolly pine (*Pinus taeda* L.) forests.

This study is part of a larger research effort to investigate the effects of six vegetation management treatments on prescribed fire intensity and subsequent relationships between fire intensity and longleaf pine growth and physiology, and soil chemical and physical properties. Our present objective is to summarize the effects of vegetation management treatment and soil type on soil bulk density, macroporosity, microporosity, total porosity, and plant-available soil water holding capacity in the A, Bt1, and Bt2 soil horizons after one application of prescribed fire.

MATERIALS AND METHODS

The study is located in two compartments of the Calcasieu Ranger District of the Kisatchie National Forest, Rapides Parish, LA. Soils in one compartment are predominantly Ruston fine sandy loam (fine-loamy, siliceous, thermic, Typic Paleudults) with some Gore silt loam (fine, mixed, thermic, Vertic Paleudalfs) (Kerr and others 1980). Soils in the second compartment are Beauregard silt loam (fine-silty, siliceous, thermic, Plinthaquic Paleudults) and Malbis fine sandy loam (fine-loamy, siliceous, thermic, Plinthic Paleudults).

In 1996, mature mixed pine forests were clear-cut in both compartments. In summer 1997, the study sites were prepared for planting by chopping and burning. In fall 1998, 12 treatment plots (22 by 22 m; 0.048 ha) were established

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

in each compartment. In March 1998, container-grown longleaf pine seedlings from one genetically improved, Louisiana seed orchard source were planted at 1.8 by 1.8 m in 12 rows of 12 seedlings each. Measurement plots were the interior eight rows of eight seedlings.

The study is a two-factor experiment with repeated measures in one factor (Neter and others 1990). Six vegetation management treatments are repeated as two blocks in each of the two compartments. Plots in compartments were blocked by apparent permeability, which was assessed by depth to the argillic horizon, texture and the presence of redoximorphic features in the A, E, and Bt1 horizons. The six vegetation management treatments are: (1) control with no vegetation management [C], (2) no burning with chemical control of woody and herbaceous vegetation [NBHW], (3) biennial prescribed burning in June [B], (4) biennial prescribed burning in June plus early chemical control of herbaceous competition [BH], (5) biennial prescribed burning in June plus early chemical control of woody competition [BW], and (6) biennial prescribed burning in June plus early chemical control of herbaceous and woody competition [BHW]. Chemical control of woody vegetation was accomplished by annual application as needed in 1998 and 1999 of Remedy® (triclopyr) to woody competition as a directed foliar spray (4-percent solution). Woody regrowth was hand-felled in 2001. Chemical control of herbaceous vegetation was done as post-plant applications of Velpar® L (hexazinone) (0.4-percent solution) in 0.9-m bands over seedlings in spring of 1998 and 1999. The first prescribed fire was applied to the B, BH, BW, and BHW plots as strip headfires in June 2000.

In fall 2002, three saplings of average height were randomly selected per measurement plot. A tractor-mounted hydraulic probe was used to extract one long soil core (5.1 cm diameter by 61 cm long) and one short soil core (5.1 cm diameter by 30.5 cm long) 1 m from the base of each of the selected saplings. Cores were placed in capped plastic liners and refrigerated until processing. Intact soil core sections were extracted from the A, Bt1, and Bt2 horizons of long soil cores and the A horizon of short soil cores. During long soil core processing, the depth to the argillic horizon (Bt1) was visually determined, and the Bt1 core increment was defined as 2 to 12 cm below this depth. Two 1-cm-long intact core sections each from the 2 to12 cm core increment, the Bt1 core increment, and the 50 to 60 cm core increment were excised using a band-saw. Similarly, short soil cores were processed so that two intact 1-cm core sections were excised from the 2 to 12 cm core increment.

From the long soil cores, two 1-cm intact core sections from each sapling and soil depth were placed in plastic rings. Rings were positioned either on an equilibrated -0.03 MPa or -1.5 MPa ceramic pressure plate. Similarly, two 1-cm intact core sections from the A horizon of the short soil cores were placed on the equilibrated -0.03 and -1.5 MPa ceramic pressure plates. Bulk density, total porosity fraction, microoporosity fraction, macroporosity fraction, and plant-available soil water holding capacity were determined with data generated by the water retention method (Klute 1986) and the core bulk density method (Blake and Hartge 1986). Bulk density (BD) was expressed as core section dry weight (g) divided by core section volume (cm^{-3}). Total porosity (TOP) was calculated by equation 1.

$$TOP = 1\text{-}[BD\ (g\ cm^{-3})/particle\ density\ (2.65\ g\ cm^{-3})] \quad (1)$$

Microporosity (MIP) was calculated by equation 2, where WATFC is the soil water content of the core section at -0.03 MPa, CSV is the core section volume, and SGW is the specific gravity of water.

$$MIP = [WATFC\ (g)/CSV\ (cm^3)]/SGW\ (1\ g\ cm^{-3})] \quad (2)$$

Macroporosity (MAP) was determined by subtracting MIP from TOP. Finally, percent plant-available soil water holding capacity (PAWHC) was calculated by equation 3, where WATFC and WATWP are the soil water content of core sections at -0.03 MPa and -1.5 MPa, respectively.

$$PAWHC = \frac{[(WATFC\ (g)/CSV\ (cm^3)) - (WATWP\ (g)/CSV\ (cm^3))]}{SGW\ (1\ g\ cm^{-3})} \times 100 \quad (3)$$

For each soil horizon, plot means of soil physical properties were analyzed by analyses of variance for a two-factor experiment with repeated measures in one factor (Neter and others 1990). Overall significance was acknowledged at $Pr \leq 0.10$. Duncan's Multiple Range test with an α of 0.10 was used to detect significant differences between means.

RESULTS AND DISCUSSION

Soil Bulk Density

Vegetation management treatment significantly affected BD in the Bt1 horizon where BD was greater on the BW, BHW, and NBHW plots than on the control plots (table 1). The BD on the BHW plots was also significantly greater than on the B plots. Values of BD in the A and Bt2 horizons were not significantly affected by vegetation management treatment.

Past research has found a variable response of BD to prescribed fire. For example, no change in BD was detected by Duvall and Linnartz (1967) and Linnartz and others (1966) after two burns in a central Louisiana longleaf pine–bluestem (*Schizachyrium* spp. and *Andropogon* spp.) forest. Moehring and others (1966) found that biennial prescribed fire slightly increased BD in the 0 to 5 cm depth but had no effect on BD in the 5 to 10 cm depth. In contrast, annual prescribed burning of an oak (*Quercus* spp.) forest in Tennessee increased BD in the 0 to 7.6 cm depth compared to no burning and burning every 5 years (Phillips and others 2000). Boyer and Miller (1994) also found that biennial winter burning of longleaf pine stands increased soil BD at the 0 to 5 cm depth. In our study, BD was consistently increased by treatments that chemically reduced woody competition. As woody vegetation was suppressed, root system proliferation and soil perturbation may have been reduced, leading to a reduction in MAP and an increase in BD. Over time, as biennial prescribed fire continues to control woody competition in our study, BD may respond similarly.

Table 1—Mean bulk density, porosity fractions, and PAWHC of the Bt1 horizon at two sapling longleaf pine sites in response to six vegetation management treatments on the Kisatchie National Forest, Rapides Parish, LA

Treatment	Bulk density	Total porosity	Macro-porosity	Micro-porosity	PAWHC
	g cm^{-3}			*percent*	
Control	1.48 c	0.441 a	0.157 a	0.281 a	6.4 a
B	1.54 bc	0.421 ab	0.129 a	0.293 a	5.3 a
NBHW	1.60 ab	0.395 bc	0.088 a	0.308 a	5.6 a
BH	1.58 abc	0.404 abc	0.133 a	0.271 a	7.5 a
BW	1.60 ab	0.401 bc	0.102 a	0.299 a	7.7 a
BHW	1.66 a	0.368 c	0.098 a	0.281 a	9.2 a

PAWHC = plant-available soil water holding capacity; B = biennial prescribed burning in June; NBHW= no burning with chemical control of woody and herbaceous competition; BH = B plus early chemical control of herbaceous competition; BW = B plus early chemical control of woody competition; BHW = B plus early chemical control of herbaceous and woody competition.

Means in a column followed by the same letter are not significantly different at $\alpha = 0.10$.

Porosity Fractions

Past research has shown that reductions in both MAP and MIP occur with repeated prescribed fire (Boyer and Miller 1994, Moehring and others 1966). In our study, MAP and MIP of the A, Bt1, and Bt2 horizons and TOP of the A and Bt2 horizons were not significantly affected by vegetation management treatment. However, TOP of the Bt1 horizon was significantly affected by vegetation management treatment (table 1). Specifically, TOP was lower on the BW, BHW, and NBHW plots than on the control plots, and TOP on the BHW plots was lower than on the B plots. Similar to BD, TOP appears to have responded negatively to the chemical control of woody competition. With long-term repeated prescribed fire and subsequent reductions in competing vegetation, soil porosity may follow the same trend.

Methods used to calculate MAP, MIP, and TOP may have influenced our ability to detect significant treatment effects. In our calculations, TOP was a function of BD; whereas MIP was a function of soil water content at field capacity, and MAP was a function of both BD and MIP. Soil water content at -0.03 MPa is strongly affected by macroporosity and soil structure (Brady and Weil 2002), which are highly variable (Fisher and Binkley 2000). The effect of this variation on soil water content at -0.03 MPa may have been too great to detect significant treatment effects in MAP and MIP.

Plant-Available Soil Water Holding Capacity

Heyward (1939) stated that burning longleaf pine forest soils seldom affected soil moisture holding capacity. However, Boyer and Miller (1994) found that biennial winter burning of longleaf pine stands reduced plant-available water. In our study, vegetation management treatment did not significantly affect PAWHC. This variable was calculated as a function of the difference between soil water content at -0.03 MPa and -1.5 MPa. As with MAP and MIP, the variation associated with soil water content at -0.03 MPa may have been too great to detect significant responses of PAWHC to vegetation management treatment. With a larger soil sample size, research will continue to evaluate the influence of vegetation management treatments on PAWHC and how potential changes in PAWHC affect longleaf pine physiology and growth.

Soil Type

The physical properties of the Ruston-Gore soil type (fine sandy loam-silt loam) and the Beauregard-Malbis soil type (silt loam-fine sandy loam) differed significantly. The BD of the A horizon was similar between soil types, but that of the Bt1 and Bt2 horizons was significantly different (table 2). The BD of the Bt1 and Bt2 horizons on the Ruston-Gore soil were 7.2 and 7.4 percent higher, respectively, than those of the Beauregard-Malbis soil. Values of MAP and MIP in the A, Bt1, and Bt2 horizons were similar between the soil types. Again, variation in MAP and soil structure may have reduced our ability to detect significant differences in MAP and MIP between soil types. Values of TOP in the A horizon were similar between soil types but in the Bt1 and Bt2 horizons, TOP was significantly lower on the Ruston-Gore soil than on the Beauregard-Malbis soil. Values of PAWHC in the A horizon were lower on the Ruston-Gore soil than on the Beauregard-Malbis soil but were unaffected by soil type in the Bt1 and Bt2 horizons.

Textural differences in the A horizon of the Ruston-Gore and Beauregard-Malbis soils (Kerr and others 1980) may have caused PAWHC differences between the two soil types. When compared to the Beauregard-Malbis soil, for example, higher clay contents in the A horizon of the Ruston-Gore soil increased the fraction of total water holding capacity that was unavailable to plants. This, in turn, led to lower PAWHC on the Ruston-Gore soil than on the Beauregard-Malbis soil.

The BD of the Bt1 horizon on the Ruston-Gore soil and the Bt2 horizon of both soil types was ≥ the root growth_limiting value of 1.6 g cm^{-3} (Kelting and others 1999, Pritchett 1979). Values of TOP in the Bt1 and Bt2 horizons continued to decrease by depth on both soil types (table 2). These inherent soil conditions may represent a barrier to

Table 2—Mean bulk density, porosity fractions, and PAWHC of the A, Bt1, and Bt2 horizon at two sapling longleaf pinesites on the Kisatchie National Forest, Rapides Parish, LA

Soil property	Soil type: Ruston-Gore	Soil type: Beauregard-Malbis
	- - - - - - A horizon - - - - - -	
Bulk density (*g cm^{-3}*)	1.38 a[1]	1.33 a
Total porosity fraction	0.485 a	0.498 a
Macroporosity fraction	0.298 a	0.236 a
Microporosity fraction	0.188 a	0.263 a
PAWHC (*percent*)	11.6 b	18.5 a
	- - - - - Bt1 horizon - - - - -	
Bulk density (*g cm^{-3}*)	1.63 a	1.52 b
Total porosity fraction	0.384 b	0.426 a
Macroporosity fraction	0.081 a	0.155 a
Microporosity fraction	0.308 a	0.271 a
PAWHC (*percent*)	4.5 a	9.4 a
	- - - - - Bt2 horizon - - - - -	
Bulk density (*g cm^{-3}*)	1.75 a	1.63 b
Total porosity fraction	0.347 b	0.388 a
Macroporosity fraction	0.067 a	0.087 a
Microporosity fraction	0.282 a	0.302 a
PAWHC (*percent*)	7.1 a	11.2 a

PAWHC = plant-available soil water holding capacity.

The soil at one site is dominated by Ruston fine sandy loam with some Gore silt loam. The soil at the second site is composed of equivalent amounts of Beauregard silt loam and Malbis fine sandy loam.

Means within a soil property and horizon followed by the same letter are not significantly different at α = 0.10.

deep root growth that appears to be more limiting on the Ruston-Gore soil than on the Beauregard-Malbis soil. This emphasizes the importance of conducting vegetation management treatments that retain optimal soil conditions for root growth in the A and Bt1 horizons.

CONCLUSIONS

Although this project was recently initiated, some effects of vegetation management treatment were apparent in the Bt1 horizon. Generally, the application of vegetation management treatments that included the chemical control of woody competition resulted in higher BD and lower TOP. We propose that as woody vegetation was suppressed, proliferation of the roots of competing vegetation, and therefore, soil perturbation, were reduced. This led to an increase in BD, a decrease in TOP, and a potential decrease in PAWHC. As long-term biennial prescribed fire continues to control woody competition, BD, TOP and PAWHC may respond similarly. It is likely that these changes in soil properties would reduce the availability of water for tree physiology and growth. Climate changes that lower soil water content could aggravate these limitations. Moreover, differences in soil properties between the two soil types in our study suggest that the potential negative effect of interaction between vegetation management treatment and climate on tree physiology and growth differs by soil type. Research will continue to monitor long-term soil responses to the vegetation management treatments in this study and evaluate relationships between soil responses and longleaf pine physiology and growth.

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LONG-TERM PRESCRIBED BURNING REGIME HAS LITTLE EFFECT ON SPRINGTAILS IN PINE STANDS OF SOUTHERN ARKANSAS

Michele L. Renschin, Lynne C. Thompson, and Michael G. Shelton[1]

Abstract—Concerns regarding the impacts of prescribed fires on faunal communities in pine stands have led to numerous studies. One soil/litter insect that may be influenced by fire is springtails, an important member of the forest floor community. A study was conducted in burned and unburned loblolly/shortleaf pine stands in southeastern Arkansas to examine whether springtail abundance, composition, and diversity were different between areas burned every 2 to 3 years over the past 20 years and areas not burned at all. Litterbags were used to collect springtails periodically over a 10-month period. Comparisons of springtail populations for the two treatments were analyzed by abundance, diversity, and similarity. A total of 5,528 individuals were collected, but only 92 percent could be identified to family; identified specimens represented 24 genera and 10 families. The prescribed fires significantly affected only one genus, *Orchesella*, which occurred in burned areas more frequently than in unburned areas. Springtail diversity was not affected by burning. Dendrograms based on Jaccard and Sorenson (Bray-Curtis) similarity indices showed no distinct grouping of the treatments. These results indicate that springtail populations on the sites are influenced more by other environmental factors than by prescribed fire.

INTRODUCTION

The health and productivity of an ecosystem can often be evaluated by quantifying the amount and diversity of organisms living in it. One group of organisms that is often used to evaluate ecosystem health and productivity is microarthropods. Microarthropods make significant contributions to processes such as decomposition, nutrient cycling, and soil formation; these processes help maintain and sustain forest productivity. Consequently, disturbances such as fire may affect these organisms and alter the processes they mediate, thus influencing forest productivity (Fritze and others 1993). Soil faunal populations are of particular importance in forest soils because they are highly important in the breakdown of forest litter (Fisher and Binkley 2000, Heyward and Tissot 1936, Weaver and Heyman 1997). One important group of soil fauna that are often studied is the collembolans or "springtails". Although very common and abundant, springtails are seldom observed because of their small size and habit of living in concealed situations. They are most commonly found in or near soil, bark, logs, fungi, and leaf litter and have populations of up to 100,000 individuals per m^2 or more (Christianson and Bellinger 1998). Although the functional contribution of collembolans in a soil community is difficult to assess, inferences can be made from their populations and species diversity. Because Collembola can be a good indicator of ecosystem health (Weaver and Heyman 1997), it may be possible to use their sensitivity to prescribed fire as a gauge of the mesofauna population as a whole. Although information is available on the impact of fire on fungi and bacteria (Fritze and others 1993), the impacts of fire on soil fauna are not well documented. There have been relatively few studies relating prescribed fire use with forest floor collembolan communities in southern pine stands (Johnston and Crossley 2002). Although intense fires affect microorganisms most dramatically, less intensive fires, as typified by prescribed burning in the South, usually have little impact, because only minor changes in soil properties are associated with fire (Wade and Lunsford 1989). A better understanding of how fire alters soil faunal populations is essential to fine-tune forest management. The following study was initiated to evaluate the effects of long-term use of prescribed fire on collembolan populations. The objective of the study was to examine whether collembolan abundance, composition, and diversity are different between burned and unburned treatments.

METHODS

Study Area and Treatments

The study was located in three compartments of the Crossett Experimental Forest in southern Ashley County, AR. Stands consisted of loblolly (*Pinus taeda*) and shortleaf pine (*P. echinata*) and are managed using uneven-aged management (Cain and Shelton 2002). Two burn treatments, established in January of 1981, were used: (1) an unburned control, and (2) an irregular interval winter burn (2 to 3 years). Six 1-ha plots were used, one unburned control, and one irregularly burned plot in each of the three compartments. Within each measurement plot, three subplots were installed for placement of litterbags.

Sampling

Litterbags (Berg and others 1998) were 30 cm by 30 cm with a mesh size of 5 mm on the top and 2 mm on the bottom. Six litterbags, each filled with 20 g of pine foliage litter collected in the fall of 1999, were placed into the field on February 24, 2000, and collected after 1, 2, 5, 7, and 10 months. A Berlese funnel was used for collembolan extraction. Collembola were sorted from the rest of the

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

extracted organisms, stored in 75 percent ethyl alcohol, and later identified. Except for the families Hypogastruridae and Neanuridae, identification was done to genus using several established collembolan keys (Bellinger and others 2003, Christianson and Bellinger 1998). Dr. Richard Snider, Department of Zoology, Michigan State University, identified voucher specimens. Additional genera and one family, which were not identified as vouchers at the date of this paper, were labeled as Morphogenus 1 - 5 and Morphofamily 1.

Statistics

Abundance of individuals occurring within treatments was compared using an analysis of variance with a split plot design (SAS Institute Inc. 1990). Diversity was measured using the Shannon-Weiner index (Colwell 1997). Cluster analysis (McCune and Medford 1999) used resemblance coefficients to evaluate the similarity of burned and unburned treatments. The unweighted pair-group method was used because it produces less distortion in transforming similarities into a dendrogram (Romesburg 1984). The Jaccard index uses presence-absence or binary (0 or 1) data, whereas the Sorenson (Bray-Curtis) index uses abundance information. The Sorenson and Jaccard indices are two of the most useful and widely-used indices (Magurran 1988).

RESULTS

A total of 5,528 individuals were collected, but only 92 percent could be accurately identified to family because some specimens were damaged or otherwise rendered unidentifiable. The 5,062 specimens identified represented 10 families and 24 genera (table 1). The overall abundance of collembolans was slightly, but nonsignificantly, greater on the burned versus unburned areas. Of the 24 genera collected, 17 had greater abundance in the burned areas. The number of specimens collected by genus ranged from 4 (*Katianna*) to 533 (*Orchesella*). Only one genus, *Orchesella*, was significantly more abundant in the burned treatments than the unburned treatments ($P = 0.022$). The burned treatments were slightly, but not significantly ($P = 0.119$), more diverse than the unburned areas. The mean Shannon diversity index was 2.21 for the burned areas and 2.08 for the unburned areas. The unburned sites exhibited higher variation in diversity across subplots than the burned sites.

Using the Jaccard index (fig. 1), both treatments of compartment 11 are the same, and those for compartments 24 and 55 are dissimilar. Using the Sorenson index, the burned area of compartment 24 separates out as very different. This result is not surprising, because the burned areas of compartment 24 exhibited high numbers of collembola (particularly *Hydroisotoma*), which would influence the Sorenson index. The Jaccard index would be more influenced by the presence of genera not found elsewhere, which occurred on the unburned areas of compartment 24.

DISCUSSION

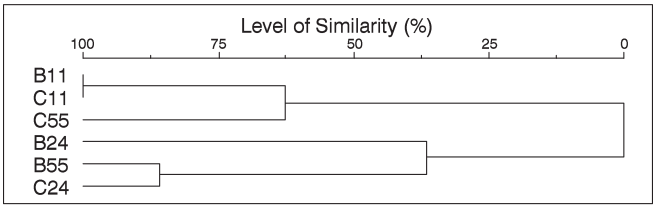
There is growing interest in using prescribed fire to restore habitat for threatened species. One concern with its use is that by promoting habitat for one species, habitat may be lost for others. Modifications of environmental conditions beyond the capacity of a species to adapt result in the loss of certain species and the addition of others (Paquin and Corderre 1997). Many of the studies occurring in the southeast have focused on groups of species that are more mobile (e.g., butterflies, flies) and less labor intensive to study. Prescriptions developed for these more mobile species may be harmful to less recognizable groups, such as the forest floor fauna, that cannot escape flames. This study began by asking the question: Does long-term prescribed fire influence collembolan populations in these stands and, if so, how? Results from other studies investigating fire effects on collembolan populations have been variable (Dindal and Metz 1976, Henig-Sever and others 2001). Many studies revealing reductions in collembolan populations are done short-term (e.g., Dindal and Metz 1976), whereas studies investigating the effects of fire after a longer period of time (such as this study) have shown rapid recovery (Kalisz and Powell 2000, Wikars and Schimmel 2001).

Table 1—Treatment totals for collembolan genera extracted from 108 litterbags from February 2000 to January 2001 in burned and unburned areas of uneven-aged loblolly-shortleaf pine stands in southern Arkansas

Family/*Genus*	Burned	Unburned	Total
Family Dicyrtomidae			
Ptenothrix	7	5	12
Family Sminthurididae			
Sminthurides	35	23	58
Family Katiannidae			
Katianna	3	1	4
Sminthurinus	82	29	111
Family Sminthuridae			
Sminthurus	97	32	129
Neosminthurus	79	193	272
Family Tomoceridae			
Tomocerus	22	10	32
Family Neanuridae[a]	157	214	371
Family Entomobryidae			
Entomobrya	82	61	143
Lepidocyrtus	276	194	470
Pseudosinella	207	273	480
Orchesella	384	149	533
Family Isotomidae			
Cryptopygus	10	4	14
Isotoma	71	52	123
Isotomurus	31	24	55
Isotomiella	27	40	67
Hydroisotoma	399	11	410
Isotomid Morphogenus 1	17	3	20
Isotomid Morphogenus 2	43	48	91
Isotomid Morphogenus 3	49	28	77
Isotomid Morphogenus 4	6	0	6
Isotomid Morphogenus 5	49	24	73
Family Hypogastruridae[a]	644	822	1,466
Morphofamily 1			
Purple Morphogenus	3	45	48
Total	2,780	2,285	5,065

[a] Individuals were not identified to genus.

Jaccard Index



Sorenson Index

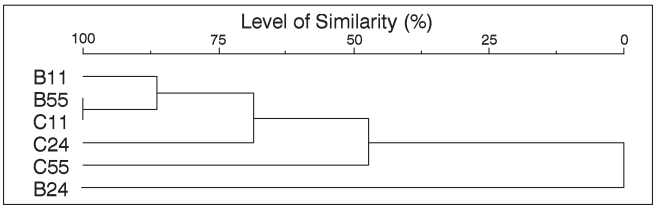


Figure 1—Dendrograms using the Jaccard and Sorenson indices to depict the relationships between collembolan genera from three burned and three unburned stands. The letter is treatment (B = Burn or C = Unburned Control), and the number identifies study site compartment [or replicate] (11, 24, and 55).

Numerically, this study shows a trend for higher abundance and diversity in burned stands than unburned stands. Although this trend was not statistically significant, it is unknown whether or not it is biologically significant. It is not apparent that there were large shifts in collembolan composition as a result of the fires. The only genus that showed significant differences between treatments was *Orchesella*. Some studies have shown certain species or families to be positively correlated with fire conditions. This study observed increases in some genera and decreases in others. In conclusion, it seems that 20 years of prescribed fire have not affected overall collembolan populations in these stands. Apparently, the collembolan populations in this study are more sensitive to environmental factors other than burning.

ACKNOWLEDGMENTS

This work was jointly supported by the USDA Forest Service and the Arkansas Forest Resources Center. We thank Dr. Hal Leichty, Dr. Richard Snider, and Dr. Paul Doruska for their technical assistance, and Kenny Davis, Steve Tackett, Adrian Grell, Rhona Jitta, Issac Foote, Ruthann Chapman, and Sam Clark for their help with work in the field and laboratory.

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SEASONAL AVIFAUNA RESPONSES TO FUEL REDUCTION TREATMENTS IN THE UPPER PIEDMONT OF SOUTH CAROLINA: RESULTS FROM PHASE 1 OF THE NATIONAL FIRE AND FIRE SURROGATE STUDY

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Abstract—We examined avian species and assemblage responses to prescribed burns and thinning in a southeastern Piedmont pine and mixed pine-hardwood forest as part of the National Fire and Fire Surrogate Study (NFFS) examining the effects of fuel reduction on forest health. Point counts conducted during the non-breeding and breeding seasons of 2000-2002 showed that winter bird species abundance and evenness (J') did not change significantly between pre- and posttreatment winter surveys. However, bird species richness increased significantly between years. No differences were found between treatments for species abundance, richness, or evenness during the breeding season. However, foliage-gleaning and canopy-nesting breeding species were detected significantly more often in thinned than burned or control sites. Nest searches and monitoring found 79 nests (thin, n = 30; burn, n = 27; control, n = 22) with a 49-percent failure rate over the 2-year period. Most of these failures (41 percent) occurred in thinned stands.

INTRODUCTION

Fire exclusion and suppression have historically been accepted as appropriate means of managing forests in the United States (Johnson and Hale 2000). As a result of these long-held philosophies, fuel loads in many U.S. forests have reached excessive proportions that increase the probability of catastrophic wildfire in many regions. The use of prescribed fire has grown slowly in popularity since World War II as a management tool to reduce fuel loads (Johnson and Hale 2000). However, due to logistical constraints that may preclude or delay burning programs (i.e., climate or smoke abatement issues), other management alternatives, such as the mechanical removal of understory and diseased or insect-infected trees, which also reduce fuel loads in forests, are needed. Thinning may mimic prescribed fire in its reduction of fuel loads by physically removing flammable materials from forested areas. However, the ecological, economic, and social impacts of using one fuel reduction technique over the other are not fully understood. To facilitate a better understanding of how such practices might affect the aforementioned impacts, the USDI-USDA Joint Fire Science Program initiated a national study to research the consequences of prescribed fire and alternative "fire-surrogate" methods, such as thinning, on fuel and fire behavior, vegetation, wildlife, entomology, pathology, soils, utilization and economics, and social science (Fire and Fire Surrogate 2000). The Clemson Experimental Forest in Clemson, SC, along with 12 other study sites nationwide, was selected to participate in the National Fire and Fire Surrogate Study (NFFS). The primary objective of the wildlife component of the NFFS is to assess the impacts that fuel reduction has on small mammal, herpetafauna, and avian communities.

There is a dearth of information regarding the impacts of prescribed fire and fuel reduction on wildlife and their habitats even though many prescribed burns are applied with the intent of benefiting various wildlife species. In the southeastern landscape, many wildlife species, including various passerines, have evolved in habitats mediated by wild and human-induced fires (Brennan and others 1998, Johnson and Hale 2000, Landers 1987). The relationships between passerines and fire management are particularly important since passerines comprise a vital ecological component in southeastern forests. In particular, early successional species, or those requiring open woodlands, may be affected by forest management activities using prescribed fire. Forest management plans and activities must consider biodiversity; therefore, it is critical that we gain a better understanding of the relationships between prescribed fire, thinning, and songbird communities in forested habitats.

METHODOLOGY

Study Area

Nine study sites were selected within the Clemson Experimental Forest (CEF) in the Upper Piedmont of South Carolina. The CEF comprises 7,100 ha of reclaimed agriculture land within three South Carolina counties, Anderson, Oconee, and Pickens. This forest exists in a nearly contiguous block and is dissected only by the city of Clemson and lakes Hartwell and Issaqueena. The CEF's northern parcel resides within the Lower Foothills of the Piedmont Foothills region, which have clayey soils that are moderately deep to thin and well-drained (Meyers and others 1986). The southern portion of the CEF is located in the Interior Plateau of the Midlands Plateau region, and the soils are usually relatively thin and composed mostly of clay (Meyers and others 1986). The nine sites selected for this study are composed mainly of naturally regenerated and planted pine stands. Dominant coniferous species include loblolly (*Pinus taeda*), shortleaf (*P. echinata*), and Virginia (*P. virginiana*) pines (Radford and others 1968).

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

The hardwood component, existing as co-dominants or as the under- and mid-story, is comprised of various oak species (i.e. *Quercus nigra*, *Q. falcata*, *Q. coccina*, *Q. alba*, *Q. stellata*), sweetgum (*Liquidambar styrraciflua*), tulip popular (*Liridendron tulipefera*), holly (*Ilex opaca*), persimmon (*Diospyros virginiana*), and blackgum (*Nyssa sylvatica*)(Radford and others 1968).

Study Sites

Based upon National Fire and Fire Surrogate protocol (Fire and Fire Surrogate 2000), sites were selected based on size, stand age, and management history. Each site was a minimum of 14 ha and comprised of a 10-ha sample area with a buffer of approximately 20 m. The sites were also judged to be in danger of uncharacteristically severe wildfire due to heavy fuel loads. None of the sites had been thinned during the last 10 years or burned (wild or prescribed) in at least 5 years. Stand ages varied from 15 to 60 years so age was used as a blocking factor to reduce variability. Within each block, three treatments—prescribe fire, thinning, or untreated control—were randomly assigned.

Treatments

Prescribed fires were applied to three study sites during early April 2001. Spot, flanking, backing, and strip head fires were set depending on site characteristics. Fire prescriptions were intended to kill a few overstory trees. Flame heights generally ranged from 0.5 to 2 m but reached 3 to 4 m in spots where fuel loading was high. Thinning occurred on three of the study sites between the months of December 2000 and February 2001. A target basal area of 18 m^2 per ha was determined sufficient to reduce the chance of severe wildfire occurring.

Avian Sampling

Non-breeding birds were censused between November 15 and January 15 of 2000 and 2001, and breeding birds were censused between April 15 and June 15 of 2001 and 2002 using a 50-m fixed radius point count method (Ralph and others 1993). Approximately three to four point-count stations were established in each of the nine study sites with a minimum of 200 m between each point and at least 100 m from the treatment boundary. Points were visited between sunrise and 1100 EST on days with no precipitation and minimal wind velocity (< 20 kph) (Ralph and others 1993). The duration of each point count was 10 minutes in which every bird heard or seen within a 50-m radius was recorded. Each point was visited twice in the winter and three times in the spring during each census period. Point-count stations and treatment areas were randomly visited and then rotated for subsequent counts to minimize within season temporal bias. Birds flying through the stands or over the canopy were not included in the analysis.

Monitoring natural nests can help determine the breeding productivity (quality) of a particular habitat unlike counts of bird densities within the same habitat (Van Horne 1983). Nest searching and monitoring took place on the nine study sites from the first week in April until the first week of July of 2001 and 2002. Sites were systematically searched for "high" activity (i.e., carrying nest material, nest building, or distraction displays) and birds exhibiting parental behaviors (Martin and Geupel 1993). Active nests were monitored every 2 to 3 days to record pertinent data like nesting species, location, nesting stage (building, laying, incubating, and nestling), number of eggs or young, and fate of nest.

Statistical Analysis

Winter and spring bird species abundance, richness (S_1; Margalef 1958), evenness (J'; Pielou 1969), and foraging and nesting guilds (Hamel and others 1982) were statistically analyzed within and between years across all treatments using PROC GLM (SAS 1996). Foraging guild assemblages were categorized as follows: (a) ground-gleaning, (b) foliage-gleaning, (c) bark-gleaning, (d) hawking, and (e) carnivore. Categorization of nesting strategies was as follows: (1) ground/shrub, (2) canopy, and (3) cavity. These guild assemblages represent important life-history traits that clarify habitat utilization for nonbreeding and breeding birds. The most abundant winter and spring species were categorized by mean-count frequency (PROC FREQ) and chi-square analysis (SAS 1996). Nest success, or survivability, was determined by the percentage of nests fledged or failed in each treatment type. To evaluate significant differences between fate of nests and treatments, PROC FREQ and chi-square analysis were used. Differences were significant at the 0.10 level.

RESULTS

Winter Birds

A total of 39 species and 1,399 individuals was detected during the winter point counts in 2000 and 2001. Winter bird species abundance was not significantly different across treatments in either 2000 or 2001 or between winters. Significant differences were detected across treatments for bird species richness ($p = 0.0955$) and bird species evenness ($p = 0.0344$) in the pretreatment winter of 2000 but not in the post treatment winter of 2001. Between year differences were detected for bird species richness ($p = 0.0231$) (table 1). Among foraging guilds in 2000 or 2001, bark-gleaners were significantly more abundant ($p = 0.0510$) in the thinned stands. Golden-crowned kinglet (*Regulus satrapa*), ruby-crowned kinglet (*Regulus calendula*), Carolina chickadee (*Poecile carolinensis*), eastern tufted titmouse (*Baeolophus bicolor*), American crow (*Corvus brachyrhynchos*), pine warbler (*Dendroica pinus*), and Carolina wren (*Thryothorus ludovicianus*)

Table 1—Comparison of mean avian species richness (S_1) between pre- and post-treatment winters at the Fire and Fire Surrogate study sites, Clemson, SC

	Burn	Control	Thin
Pre-treatment	6.46b	7.66a	5.60b
Post-treatment	10.10a	8.13a	9.26a

Values with different letters down columns are significantly different ($p \leq 0.10$)

(Sibley 2000) were the most abundant species detected during the winter. Golden-crowned kinglet abundance was significantly lower after treatment application ($p = 0.0003$) while Carolina wren ($p = 0.0028$) and pine warbler ($p \leq 0.0001$) abundance increased significantly (fig. 1).

Breeding Birds

During the spring point counts of 2001 and 2002, 2,746 individuals representing 61 species were detected. No significant differences were detected for breeding bird abundance, richness, or evenness across treatments within 2001 or 2002. However, significant differences were detected for bird species abundance ($p = 0.0253$) and bird species richness ($p = 0.0965$) between years (table 2). Increases between years were detected for ground-foragers ($p = 0.0016$) and foliage-gleaners ($p = 0.0139$). Ground-foragers increased in all of the treatment areas whereas foliage-gleaners increased in the burn and untreated control stands. Canopy-nesters and ground/shrub-nesters increased in abundance between years ($p = 0.0559$ and $p = 0.0032$, respectively). Pine warbler, red-eyed vireo (*Vireo olivaceus*), northern cardinal (*Cardinalis cardinalis*), eastern tufted titmouse, and blue jay (*Cyanocitta cristata*) (Sibley 2000) were the most abundant species recorded during the spring point counts. There was no significant increase or decrease of any of these species between the two spring sample periods.

Seventy-nine nests (2001, n = 20; 2002, n = 59) were discovered and monitored. Out of the 79 nests, 44.3 percent were successful in fledging young, 49.3 percent failed due to predation, abandonment, or weather, and 6.4 percent of the nests' fates were undetermined (table 3). The fate of nests was not determined by treatment application for either 2001 or 2002. Cavity-nesters were more successful in completing a nesting attempt than ground/shrub- or canopy-nesters.

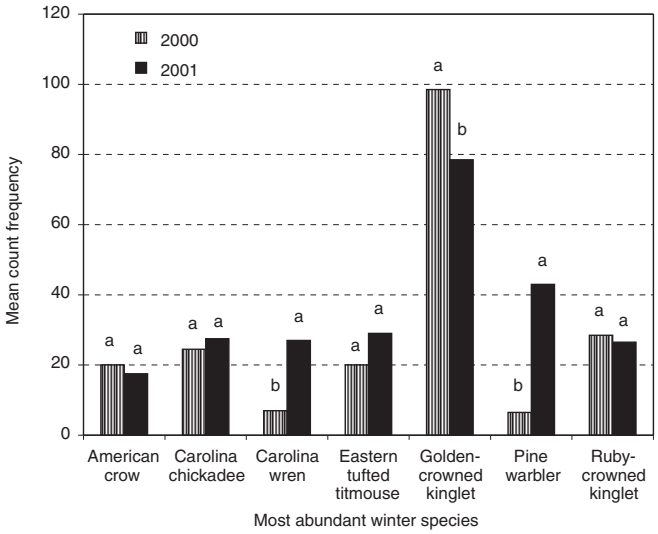

Figure 1—Comparisons between the winter of 2000 and 2001 of the most abundant species detected. Columns with different letters for each species grouping are significantly different ($p \leq 0.10$).

Table 2—Comparisons of spring avian species abundance and richness (S_1) means between years at the Fire and Fire Surrogate study sites, Clemson, SC

Treatments	Burn	Control	Thin
Abundance 2001	21.66b	23.66b	25.00a
2002	28.66a	26.66a	25.00a
Richness 2001	10.06b	10.87a	11.18a
2002	12.27a	11.58a	10.56a

Values with different letters down columns are significantly different ($p \leq 0.10$)

Table 3—Number of nests and nest survivorship for treatments by year at the Fire and Fire Surrogate study sites, Clemson, SC

Treatment	Successful	Failed	Unknown	Total
		2001		
Burn	0	2	0	2
Control	2	1	1	4
Thin	4	6	4	14
Total nests (%)	6 (30)	9 (45)	5 (25)	20 (100)
		2002		
Burn	14	10	1	25
Control	8	9	1	18
Thin	7	9	0	16
Total nests (%)	29 (49)	28 (48)	2 (3)	59 (100)

CONCLUSIONS

Initial response data on the effects of prescribed fire and thinning as fuel reduction treatments on breeding and winter bird communities showed that the treatments alter aspects of the forest that may favor certain species or assemblages. In the case of winter bird species richness, treatments diversified the forest structure, thereby supporting a broader range of bird species during the winter months. However, these changes may not favor other species. Significantly fewer golden-crown kinglets were recorded in the winter of 2001 after treatment applications. Golden-crowned kinglets breeding densities have been observed to decrease in burned or logged areas or habitats with open canopies (Ingold and Galati 1997). Carolina wren abundance increased significantly during the winter of 2001. This change may be due to an increase in coarse woody debris on the thin sites, which offer cover and foraging sites. Pine warbler abundance also increased after treatment application. These increases may be attributable to reductions in understory cover that the species may favor during the nonbreeding season (Rodewald and others 1999). The thin and burn treatments probably attracted more pine warblers because those treatments had reduced understories yet retained a developed overstory pine component.

Breeding bird abundance and richness changed between years, which may be due to the change in vegetation composition over time. The lack of an observable response across treatment types by breeding birds may be due to a number of factors including the limited temporal scope, the study, southern pine beetle (*Dendroctonus frontalis*) (Payne 1980) infestation, landscape context, or a multitude of other variables that were not measured. The application of prescribed fire and thinning increased abundance of certain foraging and nesting guilds like foliage-gleaners and ground/shrub-nesters. Both of these guild types include species that are either neotropical migrants and/or early-successional species. Many species of both assemblages have undergone declines in many regions (Robbins and others 1989).

In terms of songbird productivity, habitat manipulation may enhance the quality and quantity of nesting habitat for many bird species. However, it may also predispose treated habitats to increased predation events (Barber and others 2001, Duguay and others 2000). We found higher rates of nest failures in thinned sites (41 percent) compared to the burned (32 percent) and untreated controls (27 percent). It is possible that most of the nests failed due to predation, as it has been found to account for up to 80 percent of nest losses in other studies (Martin 1992, Martin 1993). However, without additional observations or data (such as remote cameras or predatory species densities), it is difficult to determine fates by nest remains (Lariviere 1999).

Continued research over the next 2 to 3 years is likely to show additional responses by avian species and assemblages to treatment application because vegetation will continue to respond to increased light levels and decreased competition. However, as succession progresses and fuel loads accumulate, the bird community will probably return to pretreatment composition.

ACKNOWLEDGMENTS

This is Contribution Number 30 of the National Fire and Fire Surrogate Project (NFFS), funded by the United States Joint Fire Science Program.

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Natural Pine Management

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ECONOMIES OF SCALE AND FOREST MANAGEMENT IN MISSISSIPPI

Andrew James Londo and Donald Leo Grebner[1]

Abstract—Mississippi is the leading producer of timber in the south- central region of the United States with a combined 78 billion board feet of hardwood and softwood sawtimber harvested annually. Most of this timber comes from private nonindustrial forest land, which accounts for 66 percent of the State's 18.6 million acres of forest land. The forest products industry contributes $11.4 billion annually to the State economy. Between 1978 and 1996, the number of forest landowners in Mississippi has increased from 185,000 to just over 368,000. As the number of landowners has increased, the average size of forest properties has dropped from approximately 76 to 50 acres. This reduced forest property size increases the costs associated with forest management. For landholdings smaller than 10 acres in size, there is an even larger disparity in management costs. Although these smaller parcels can be harvested, site preparation and planting costs may be an obstacle to forest management. The education level and motivation of this large and diverse ownership group also plays a role in forest management. Recommendations for addressing these issues lie primarily in landowner education and economic incentive programs. Landowner knowledge of forest valuation, management, and sources of assistance will be critical to improving and maintaining productivity of these forests.

INTRODUCTION

Mississippi is a heavily forested State. Approximately 18.6 million acres of forest land accounts for 66 percent of the State's land area. Forestry and the forest products industry contribute $11.4 billion to the State economy (Munn 1997). Private nonindustrial forest (PNIF) landowners own 66 percent of the forest land in the State. Since 1978, the number of forest landowners in Mississippi has increased from 185,000 to 368,000 in 1996 (Birch 1996). Along with this increase in landowners, average land holdings have dropped from 76 to 50 acres in size. This can create a system of fragmented ownerships and diseconomies of scale for natural resource management costs (Fleury and Blinn 1996). Much of the forest land in the United States was originally in large blocks, and these blocks have been continuously fragmented over the years (Vessels 1996). Main causes of forest fragmentation include increasing numbers of forest landowners, urban sprawl, and agricultural development (Drzyzga and Brown 1998, Hill 1985, Rudis 1995). Many new forest landowners were raised in urban areas and have different management goals from traditional timber production (Dwyer and Stewart 1998, Shepard 2000). Fragmentation may also increase demands on forest land for recreation and wildlife habitat (Hill 1985, Schmidt and Raile 1998).

Recent increases in stumpage prices of southern pine sawtimber may have increased timber harvesting in the South. However, many landowners lack a basic understanding of forest valuation and management. An understanding of these two concepts is extremely important if smaller forest landowners are to receive the socio-economic benefits of their forest land. The purpose of this paper is to discuss the influence of forest fragmentation on forest management costs in Mississippi. In addition, programs offered by the Mississippi State University Extension Service, and other State and Federal programs to assist and educate PNIF landowners will be discussed.

METHODS

Cost Data for Mississippi

Average costs per acre are provided by the Mississippi Forestry Commission for the 1998 Forest Resources Development Program (FRDP). FRDP was established in 1974 to increase timber production on NIPF lands. It provides cost-share assistance to eligible landowners for certain forest improvement practices (Varnedoe 1993). Any private landowner, association, or agency of the State is eligible for FRDP funds except for corporations that manufacture forest products or provide public utilities. In addition, land on which Federal cost-share monies have been used is not eligible for FRDP assistance. FRDP-approved practices discussed here include mechanical and chemical site preparation, prescribed burning, and pine and hardwood planting.

The Mississippi Forestry Commission allows FRDP funds to be available for both heavy and light mechanical and chemical site preparation. Differences in cost and cost-share payments are dramatic, with heavy mechanical site preparation reimbursed at $40 per acre and light mechanical site preparation at only $5 per acre. However, all mechanical and chemical site preparation cost-share data have been lumped together. Because of this, values reported here for both mechanical and chemical site preparation will be assumed to be for heavy site preparation. The Mississippi Forestry Commission has evaluated 1998 forest management costs and cost-share data by landholding size. These landholding sizes are as follows: 1 to 4 acres, 5 to 9 acres, 10 to 19 acres, 20 to 49 acres, 50 to 99 acres, and >100 acres.

RESULTS AND DISCUSSION

Mechanical Site Preparation

Average mechanical site preparation costs by landholding size for Mississippi are presented in figure 1. Costs for small landowners (1 to 4 acres) are highest at approximately $170 per acre. Costs for landholdings over 100

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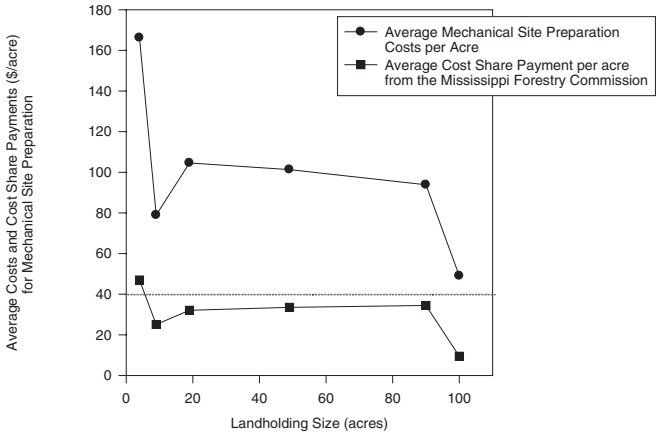
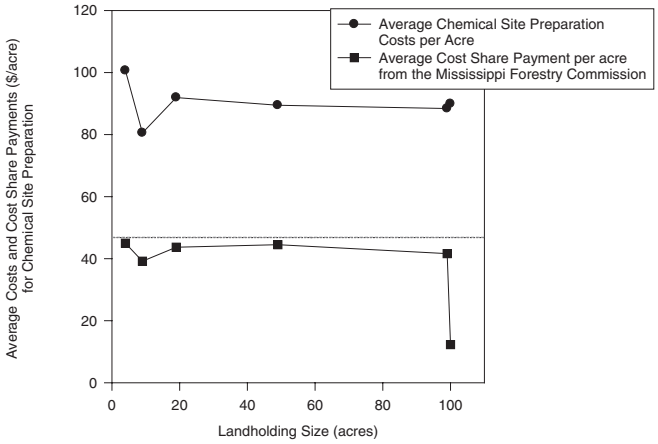
Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.



*Horizontal line represents maximum cost share payment allowable for mechanical site preparation ($40.00 per acre) by the Mississippi Forestry Commission.

Figure 1—Average costs and cost-share payments for mechanical site preparation by landholding size in Mississippi in 1998.



*Horizontal line represents maximum cost share payment allowable for chemical site preparation ($45.00 per acre) by the Mississippi Forestry Commission.

Figure 2—Average costs and cost-share payments for chemical site preparation by landholding size in Mississippi in 1998.

acres are lowest at approximately $50 per acre. Generally, costs decrease as ownership size increases, with the exception of landholdings between 5 and 9 acres, which are the second lowest values presented.

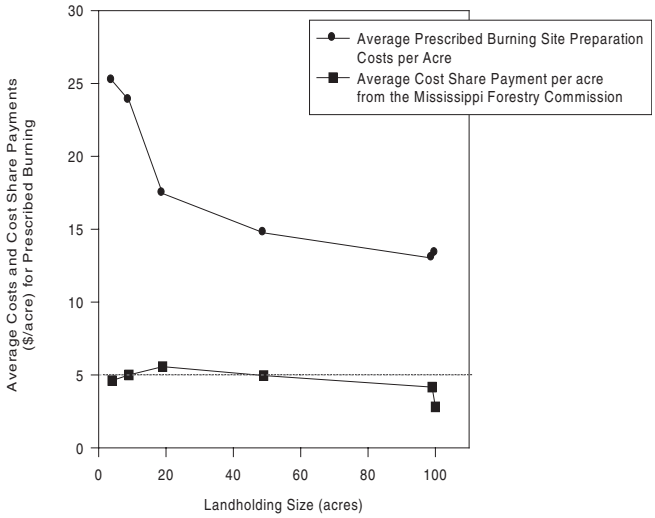
Cost-share payments per acre are highest for the 1 to 4 acre size class with a general decrease in cost-share payment with increasing acreage. Cost-share payments for the 1 to 4 acre size class are greater than the $40 per acre maximum payment allowed. Although there is no clear reason for this, it is possible that some Section 16 land was reimbursed at a full 100 percent of expenses incurred. By State law, every 16th section is set aside for funding schools in that county. FRDP cost-share activities on Section 16 lands are 100 percent reimbursed to the counties.

Chemical Site Preparation

Chemical site preparation costs and cost-share payments showed trends similar to mechanical site preparation with the 5 to 9 acre size class exhibiting the lowest costs. However, there was only an approximate $20 per acre difference between the smallest and largest landholding sizes (fig. 2). Cost-share payments for the largest landholding size decreased dramatically compared to the other landholding sizes. A possible reason for this could be that more light chemical site preparation work was performed on these larger landholdings, resulting in a decrease in payments.

Prescribed Burning Site Preparation

Costs varied greatly for prescribed burning with the highest costs occurring in the smallest landholding sizes, and steadily decreasing with increasing acreage. Cost-share payments were also very similar for all landholding sizes (fig. 3). Increased costs associated with smaller acreages include higher fire lane construction and maintenance costs along with the cost of moving equipment to these smaller sites. The use of prescribed burning is decreasing in Mississippi due to increased costs of liability insurance and more restrictive environmental limitations, which serve to limit days burning can occur.



*Horizontal line represents maximum cost share payment allowable per acre for prescribed burning site preparation ($5.00 per acre) by the Mississippi Forestry Commission.

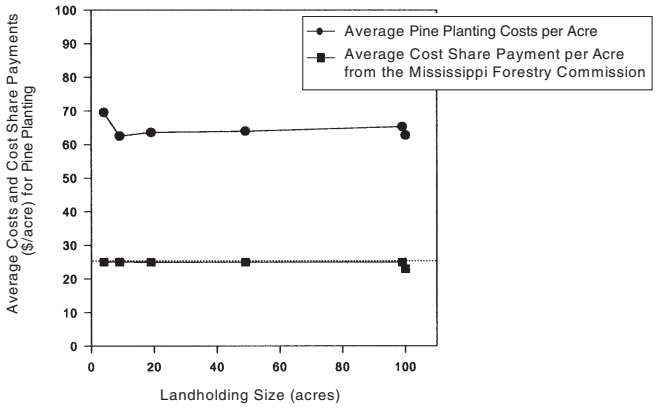
Figure 3—Average costs and cost-share payments for prescribed burning site preparation by landholding size in Mississippi in 1998.

Pine Planting

Pine planting costs and cost-share payments are consistent across all landholding sizes (fig. 4). Often, smaller landowners can have their land planted when a contractor is planting other sites in the area. Cooperation and communication among all landowners in an area for planting and site preparation work can reduce costs for smaller landowners.

Hardwood Planting

Hardwood planting costs were higher and more varied than pine (fig. 5) for several reasons. Hardwood seedlings are more expensive than pine seedlings in part because they are more difficult to grow in a nursery, and, as a consequence, fewer nurseries grow them for forest planting. Secondly, due to more lateral roots and an overall larger



*Horizontal line represents maximum cost share payment allowable per acre for pine planting ($25.00 per acre) by the Mississippi Forestry Commission.

Figure 4—Average costs and cost-share payments for pine planting by landholding size in Mississippi in 1998.

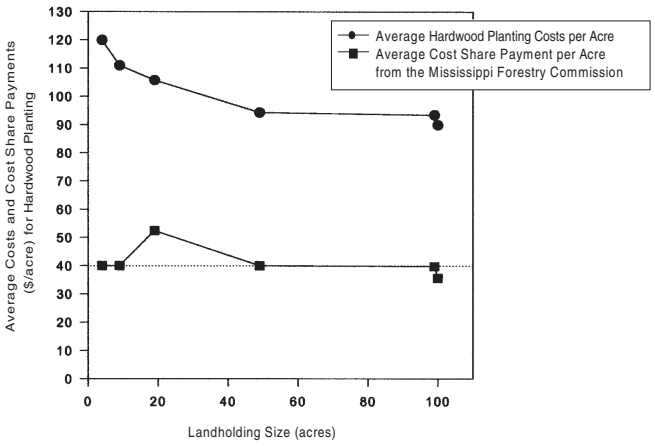


Figure 5—Average costs and cost-share payments for hardwood planting by landholding size in Mississippi in 1998.

root mass, hardwood seedlings are more difficult to plant, thus increasing costs.

CONCLUSIONS

In summary, all the management practices discussed in this paper are more expensive for smaller landowners (1 to 4 acres) than for larger landowners (≥ 100 acres). As fragmentation continues and landholding sizes become smaller, these increased management costs may become more pronounced (Leatherberry 1998). In addition to specific management costs, forestry assistance costs also increase with decreasing landholding size (Munn 2001). The average forest landholding size in Mississippi is currently 50 acres, down from 76 acres 25 years ago. The number of forest landowners has nearly doubled during this same period. However, at the same time, the total forested acreage in the State has increased. This is largely due to the conversion of former agricultural land to forest land through the Conservation Reserve Program.

The average landholding size appears to be sufficiently large to balance the economies of scale for forest management activities. However, the decrease in landholding size over the last 25 years is likely to continue. Since most of the State's forest land is controlled by NIPF landowners, changes in this ownership group will have an effect on the forest management costs and the overall forest products industry in Mississippi.

ACKNOWLEDGMENTS

This manuscript has been approved as publication number 120236 of the Forest and Wildlife Research Center, Mississippi State University.

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MICROCLIMATIC CONDITIONS AFTER REPRODUCTION CUTTING IN SHORTLEAF PINE STANDS IN THE OUACHITA MOUNTAINS

James M. Guldin and James P. Barnett[1]

Abstract—Automated weather stations collected microclimatic data over a 4.75-year period in six reproduction cutting treatments—a clearcut, two shelterwoods, a group selection, a single-tree selection, and an unmanaged control—in shortleaf pine stands in the Ouachita Mountains of west-central Arkansas. Treatment means for air temperature at 15 cm, soil temperature, solar radiation, and windspeed were greater for the clearcut than for the group selection, whereas air temperature at 2 m and vapor pressure deficit were markedly higher for the group selection treatment. A thermal inversion effect might be the cause. Retaining overstory hardwoods in the pine-hardwood shelterwood led to increased vapor pressure and soil moisture deficits vs. the pine shelterwood alone. Solar radiation in the single-tree selection was three times greater than in the unmanaged control. Foresters who employ natural regeneration to meet the landowner's goals should be aware of important microclimatic attributes of reproduction cutting methods at their disposal.

INTRODUCTION

A long-term reproduction cutting study was installed in the Ouachita Mountains of west-central Arkansas and eastern Oklahoma in 1993. The objective of the study was to test different reproduction cutting methods that rely on natural regeneration in shortleaf pine (*Pinus echinata* Mill.) and pine-hardwood stands of the region (Baker 1994, Guldin and others 1994). Controls in the study included a clearcut treatment and an unmanaged treatment. Even-aged reproduction cutting methods tested included two variations of the seed-tree method and three variations of the shelterwood method. Uneven-aged reproduction cutting methods included two variations of the group selection method and four variations of the single-tree selection method.

An important question in the study is the degree to which microclimatic conditions are altered as a result of different treatments. The probability of seedling mortality is highest in the first growing season after germination. Planted pine seedlings have the luxury of spending that first year in an irrigated and fertilized nursery environment that minimizes mortality. Pine seedlings of natural origin spend their first year within a more difficult microclimatic condition established by the structure of the stand in which their germination occurred. The forester who employs natural regeneration to meet the landowner's goals can alter the microclimatic condition by the choice of reproduction cutting method, but the magnitude and attributes of that effect are poorly understood in shortleaf pine and pine-hardwood stands in the Ouachita Mountains. Thus, quantification of microclimatic conditions under different reproduction cutting methods will be of interest to foresters who manage for natural regeneration.

Three guiding questions were posed with this dataset. First, to what degree do conditions in a group selection opening approximate those in a clearcut? The group selection method is often advocated as a possible substitute for the clearcutting method, and these data can be used to address whether group openings have the same microclimatic attributes as clearcuts. Second, how do adding residual overstory hardwoods affect microclimatic conditions in a pine shelterwood? It has been reported that 1 square foot of hardwood basal area equals 2 square feet of pine basal area given the larger crowns that a hardwood of given diameter at breast height has relative to a pine of equivalent diameter (Baker and others 1996). An investigation of microclimatic conditions in the shelterwood treatments may enlighten this observation. Third, in what ways does the single-tree selection method differ from unmanaged control conditions? Single-tree selection is often suggested as a preferred method for use in managing forest stands, because it promotes conditions that are most similar to those found in an unmanaged stand. Microclimatic data might also promote an examination of this relationship in a quantitative manner.

In this paper, the results of a 4.75-year study are presented for a set of ecologically important microclimatic variables under a variety of reproduction cutting methods applied in shortleaf pine and pine-hardwood stands in the Ouachita Mountains of west-central Arkansas and eastern Oklahoma.

METHODS

The characterization of microclimatic conditions following different reproduction cutting methods has been limited not only by the cost of the appropriate equipment but also the limited number of studies in which a variety of reproduction cutting methods have been imposed. An early decision was made to use an unreplicated sample design, acknowledging that the descriptive information available across a number of treatments might be more informative than data from a limited number of replicates. Six treatments were selected for study, and one stand per treatment was selected for instrumentation. The selected treatments and the target pine and hardwood residual basal areas after cutting are listed in table 1. Stands were included in the study based on their physical proximity, such that all stands were located within a 25-km radius of Mount Ida, AR.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Automated weather stations were used to quantify microclimatic conditions in the stands under study. One weather station was installed in each stand, on the midslope of a typical south- to southwest-facing aspect. Elevations varied from 200 m to 300 m. Weather stations were powered using a rechargeable marine battery, and a solar panel was used to recharge the battery. The basic elements of the weather station consisted of Omnidata products, including the EL-924 Easylogger and EA-110 Multiplexer, the EA-602 Polycorder, and the EM-9064 Data Storage Pack. Other sensors used to collect data for the variables in the study included:

- Omnidata ES-120, Vaisala temperature and relative humidity sensors
- Omnidata ES-060-SW, Soil and water temperature probe
- Omnidata ES-230, Licor pyranometer
- Omnidata ES-160, Sierra Misco rain gauge
- Omnidata ES-040, Anemometer
- Omnidata ES-270, Larson Watermark soil moisture block.

The microclimatic variables measured with these instruments were:

- windspeed, measured 3 m aboveground (km/hour)
- rainfall, collected 3 m aboveground (cm/hour)
- relative humidity, measured 2 m aboveground (percent)
- solar radiation, measured 2 m aboveground (watts/m^2)
- air temperature, measured 2 m and 15 cm aboveground (^oC)
- soil temperature, measured at a depth of 7.5 cm (^oC)
- soil moisture deficit, measured at a depth of 7.5 cm and 22.5 cm (bars).

Vapor pressure deficit (kPa) was calculated using relative humidity and air temperature at 2 m. Sensors for these microclimatic variables were wired to a multiplexer unit that relayed the signal from the sensor to the data logger. Every hour, the data logger triggered the recording of sensor readings and saved the data in the memory of the data storage module. Once a month, technicians visited the sites for maintenance; the module containing the data was swapped with a fresh module with a cleared memory. Data were then returned to the lab, downloaded, and processed.

Table 1—Treatment methods and the associated target residual basal area for pine and hardwood[a]

Treatment method	Target residual basal area	
	Pine	Hardwood
	- - - - - - - m^2/ha - - - - - - -	
Clearcutting	0	0.46 – 1.15
Group selection	13.8	0[a]
Shelterwood, pine	9.2	0.46 – 1.15
Shelterwood, pine-hardwood	6.9	2.3
Single-tree selection	11.5	2.3
Unmanaged control	22.9	6.9

[a] No residual pines or hardwoods were retained in group selection openings. Pines were harvested in the matrix of the group selection stands; the target residual basal area of 13.8 m^2/ha is an average across the entire stand, encompassing both the area in groups and the matrix between groups.

Data were collected at the stations over a 4.75-year period. The initial setup of the stations was in July 1994, and stations were decommissioned in April 1998. The maximum number of hourly observations potentially recorded in the dataset during this period was approximately 250,000. However, interruptions in service at one or more of the stations frequently occurred during the study. Prominent reasons for these disruptions included activity of wild animals, activity of domestic animals, and vandalism. Some of these interruptions occurred for all variables in the study, such as when power to the storage modules was interrupted. Others occurred when a given sensor was affected by some exogenous interference. A partial list of disruption events includes the following:

- “soil moisture blocks and temperature sensors pulled up by cows” (October 1994)
- “marine battery stolen” (January 1995, May 1996, October 1996, and December 1996)
- “solar panel shot 7 times” (January 1995)
- “soil probe wires gnawed completely through” (May 1996)
- “cables into Easylogger cut” (November 1996)
- “steel data enclosure shot twice, bullets missed data logger” (December 1996)
- “muzzleloader bullet holes in solar panel and steel case—Easylogger and multiplexer destroyed” (January 1997)

The effect of this activity was exacerbated because scheduled maintenance calls were made only on a monthly basis. Thus, service disruptions were typically not detected until either the next regularly scheduled monthly visit in cases of obvious damage or vandalism, or until the initial inspection of data after downloading for sensor malfunctions not apparent from visual inspection. Thus, the dataset has extended periods during which measurements of one or more variables were not taken at one or another of the sites. The varying interruptions in service present a complication in comparing conditions at the different stations. For purposes of the comparisons reported here, it was decided to include those observations for a given variable only for a given date and time when that variable was being recorded at all six stations concurrently between 1994 and 1998. No variable was concurrently collected on all six stations more than about 33 percent of the time. For example, in the analysis of treatment means by month, data for the month of July were not presented because there was no point in any of the 4 July months during the study when all six stations were concurrently collecting data.

Statistical analyses conducted on the dataset included the calculation of means and standard deviations for each treatment for the duration of the study—by year, by month, and by hour. Tests of statistical significance and mean differences were made using one-way analysis of variance and Tukey’s mean separation test. Because data were analyzed only for those periods when all six stations were operating concurrently, comparisons for a given variable across year, month, and hour may not be directly comparable from one interval to the next. For example, the mean air temperature at 2 m may vary from year to year if

data from a given month were concurrently collected during one year but not another. Despite this limitation, it was thought that comparisons among treatments for a given variable in the dataset would be illuminating, especially given that all such comparisons are based on common periods of data collection across all six treatments.

RESULTS

Air Temperature at 2 m

The group selection treatment was significantly hotter than all other treatments in the study [table 2(A)]. This trend did not initially appear until 1996 but lasted through the end of the study. There was also a monthly effect, such that the group selection treatment was significantly warmer than other treatments from February through October but not during November, December, or January. The diurnal effect was most striking (fig. 1) in which significantly warmer temperatures in the group selection treatment were observed from 1200 hours to 2000 hours, inclusive.

Air Temperature at 15 cm

The clearcut had the highest air temperature at 15 cm, followed by the single-tree selection and the pine-hardwood shelterwood, and then the remaining three treatments [table 2(B)]. The mean temperature difference between the hottest and coldest treatments was slightly less than that for the air temperature at 2 m variable. The diurnal effect (fig. 2) shows that the group selection treatment exceeds all other treatments during a few midafternoon hours, the clearcut is the hottest treatment in the morning hours, the group selection is hottest in the midafternoon hours, and the unmanaged control is the hottest throughout the night. In all treatments, the air temperature at 15 cm was greater than the air temperature at 2 m, except for the late afternoon–early evening readings from the group selection treatment.

Soil Temperature at -7.5 cm

The clearcut had the highest soil temperature of all treatments at depth 7.5 cm, and the unmanaged control and group selection treatments had the lowest soil temperature at that depth [table 2(C)]. The range in means was from 18.6 to 16.4 °C. For each treatment, the mean soil temperature was higher than the corresponding mean for air temperature at 15 cm. However, relative to the air temperature readings, the diurnal range of variation had a lower difference between the midafternoon high reading and the midmorning low reading (fig. 3).

Relative Humidity at 2 m

The pine shelterwood had the highest mean relative humidity, followed by the unmanaged control; the clearcut had the lowest mean value [table 2(D)]. The diurnal pattern in relative humidity readings showed a maximum at 0700 hours and a minimum at 1500 to 1600 hours, with a difference of 30 percent between maximum and minimum values (fig. 4). The pine shelterwood showed the highest relative humidity levels and the clearcut the lowest values, at night. Conversely, the unmanaged control had the highest relative humidity values and the group selection the lowest values, during the day.

Vapor Pressure Deficit at 2 m

Vapor pressure deficit (VPD) integrates air temperature and relative humidity into a variable that reflects the dryness of the air and the physiological plant response in terms of transpiration potential. In this study, mean VPD was highest for the group selection treatment and lowest for the unmanaged control treatment [table 2(E)]. The greatest diurnal variation was found in the group selection treatment (fig. 5), which varied by more than 2 kPa. All other treatments varied diurnally by 1 kPa or less. Figure 5 also shows the peak VPD readings from 1200 hours to 1900 hours, which parallels the peak reported for air temperature at 2 m in the group selection treatment.

Soil Moisture Deficit at -7.5 cm

The soil moisture deficit (SMD) for the 7.5-cm soil depth varied from 4.73 bars in the unmanaged control to 2.34 bars in the clearcut, with significantly different means for each treatment [table 2(F)]. The seasonal effect of SMD was most pronounced (fig. 6). SMDs were < 4 bars for all treatments during the winter and spring months but increased dramatically during summer and early autumn. All treatments reached their mean monthly maximum in August, except for the group selection treatment, which reached its maximum in September. For the 2-month period in August and September, all treatments except the clearcut had monthly mean SMDs exceeding 6 bars. These data point to the SMD to which seedlings will be exposed in the upper layers of the soil in late summer on these sites.

Soil Moisture Deficit at -22.5 cm

The SMD data at 22.5-cm depth showed greater variation than the shallow SMD data. Mean SMDs varied from a high of 6.22 bars in the pine-hardwood shelterwood to lows of 1.71 and 1.73 bars in the pine shelterwood and the clearcut treatments, respectively [table 2(G)]. Monthly data also vary widely (fig. 7). Mean SMD values exceed 6 bars from March through September in the pine-hardwood shelterwood, suggesting erroneous readings from the soil moisture block in that stand. Otherwise, the means by treatment and annual patterns indicate a slightly lower SMD at the 22.5-cm depth compared with the 7.5-cm depth.

Solar Radiation at 3 m

There was greater than a fourfold difference in solar radiation across the treatments, with the mean radiation level highest in the clearcut and lowest in the unmanaged control [table 2(H)]. The diurnal trend showed very similar trends for the clearcut and group selection (fig. 8). The other four treatments showed irregularities in the diurnal pattern: an unusual decline in the afternoon observations from the pine-hardwood shelterwood and marked interruptions in the shape of the normal curve for the single-tree selection and especially the pine shelterwood. The number of observations collected (for each treatment, n = 532 at 1400 hours, n = 532 at 1500 hours, and n = 530 at 1600 hours) suggests the decline in some treatments is due to the physical presence of something that casts shade on the pyranometer, such as a nearby residual overstory or midstory tree.

Table 2—Number of observations per treatment, standard errors, and results of Tukey's mean separation tests by treatment for variables in the study

Treatment		Mean	SE	Dif.	Treatment		Mean	SE	Dif.
	no.					*no.*			
	A. Air temperature, 2 m, °C					**F. Soil moisture deficit, -7.5 cm, bars**			
GSP	14,953	17.17	0.095	A	UC	7,102	4.73	0.054	A
CC	14,953	15.96	0.073	B	SWW	7,102	4.44	0.060	B
STS	14,953	15.80	0.073	B	STS	7,102	3.93	0.061	C
UC	14,953	15.70	0.070	B	GSP	7,102	3.37	0.055	D
SWW	14,953	15.20	0.075	C	SWP	7,102	3.09	0.051	E
SWP	14,953	15.01	0.075	C	CC	7,102	2.34	0.043	F
	B. Air temperature, 15 cm, °C					**G. Soil moisture deficit, -22.5 cm, bars**			
CC	13,935	17.66	0.095	A	SWW	7,146	6.22	0.075	A
SWW	13,935	17.07	0.092	B	STS	7,146	3.85	0.059	B
STS	13,935	16.96	0.090	B	GSP	7,146	3.34	0.054	C
GSP	13,935	16.28	0.097	C	UC	7,146	2.02	0.030	D
UC	13,935	16.28	0.075	C	CC	7,146	1.73	0.019	E
SWP	13,935	16.04	0.084	C	SWP	7,146	1.71	0.030	E
	C. Soil temperature, -7.5 cm, °C					**H. Solar radiation, watts/m²**			
CC	12,258	18.6	0.068	A	CC	12,800	181.4	2.48	A
STS	12,258	18.0	0.069	B	GSP	12,800	162.2	2.43	B
SWP	12,258	17.6	0.060	C	SWW	12,800	159.3	2.50	B
SWW	12,258	17.4	0.056	C	STS	12,800	148.2	2.27	C
UC	12,258	16.6	0.057	D	SWP	12,800	114.00	1.81	D
GSP	12,258	16.4	0.063	D	UC	12,800	42.9	0.81	E
	D. Relative humidity, percent					**I. Hourly rainfall, cm/hour**			
SWP	15,002	82.3	0.186	A	SWP	13,215	0.021	0.0014	A
UC	15,002	81.2	0.155	B	GSP	13,215	0.019	0.0012	AB
GSP	15,002	79.0	0.181	C	UC	13,215	0.018	0.0013	AB
SWW	15,002	78.4	0.175	CD	STS	13,215	0.015	0.0011	BC
STS	15,002	78.2	0.175	D	SWW	13,215	0.013	0.0008	C
CC	15,002	77.4	0.170	E	CC	13,215	0.011	0.0007	C
	E. Vapor pressure deficit, kPa					**J. Windspeed at 3m, km/hour**			
GSP	14,953	0.75	0.010	A	CC	11,403	4.23	0.042	A
CC	14,953	0.55	0.005	B	SWW	11,403	1.52	0.021	B
STS	14,953	0.53	0.006	B	STS	11,403	1.31	0.021	C
SWW	14,953	0.52	0.006	B	SWP	11,403	1.09	0.017	D
SWP	14,953	0.49	0.006	C	GSP	11,403	1.02	0.017	D
UC	14,953	0.43	0.004	D	UC	11,403	0.67	0.011	E

SE = standard errors; Dif. = results of Tukey's mean separation tests; CC = clearcut; GSP = group selection; STS = single-tree selection; SWP = shelterwood with pine residuals; SWW = shelterwood with pine and hardwood residuals; UC = unmanaged control.
In the Tukey's test, different letters in a column denote statistically significant mean comparisons among treatments.

Hourly Rainfall

Means for hourly precipitation over the duration of the study varied by a factor of two, with the pine shelterwood receiving the most precipitation and the clearcut receiving roughly half that amount [table 2(I)]. The hourly values from table 2(I) translate to 182 and 91 cm annually, which bracket the generally accepted values of 137 to 152 cm of precipitation annually in the Ouachita Mountains (Skiles 1981). The annual precipitation pattern is of interest; although the monthly means vary by treatment the trends from month to month reflect the lower amounts of rainfall experienced in the region during the summer months (fig. 9).

Windspeed at 3 m

Significant differences in windspeed were observed among treatments, though one treatment stands out. All treatments except the clearcut had mean windspeeds < 1.6 km/hour [table 2(J)]. The clearcut has a mean windspeed of 4.23 km/hour, nearly three times the mean windspeed of the pine-hardwood shelterwood and more than six times the mean windspeed of the unmanaged control [table 2(J)]. The diurnal pattern shows that the hourly distribution of windspeed is generally linearly distributed at low levels at night between 2000 hours and 0800 hours, but then follows a normal distribution during the day from 0800 hours to

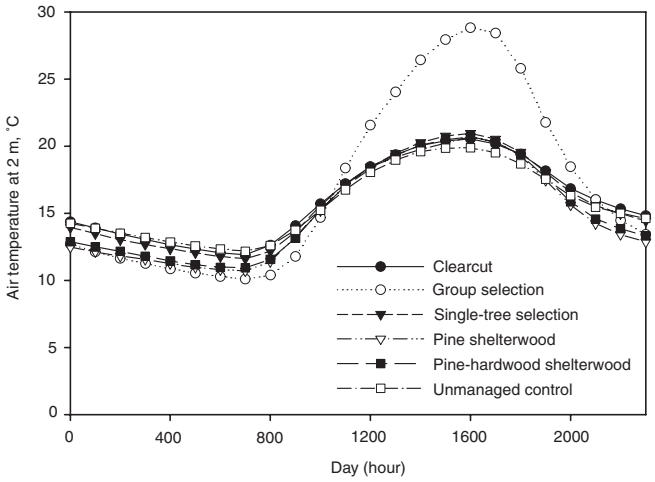

Figure 1—Mean hourly air temperature at 2 m by treatment.

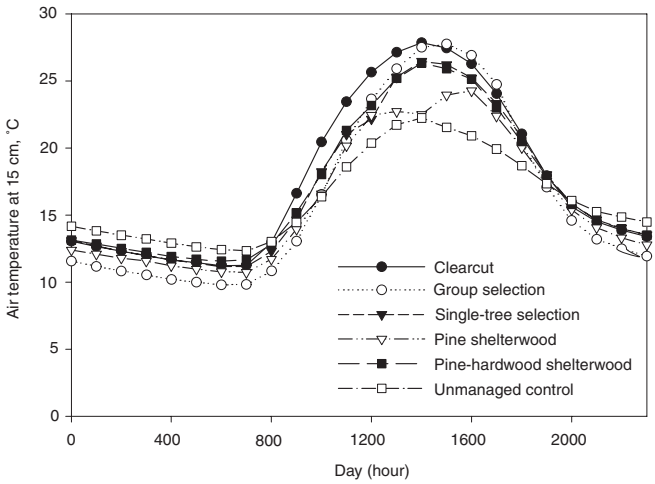

Figure 2—Mean hourly air temperature at 15 cm by treatment.

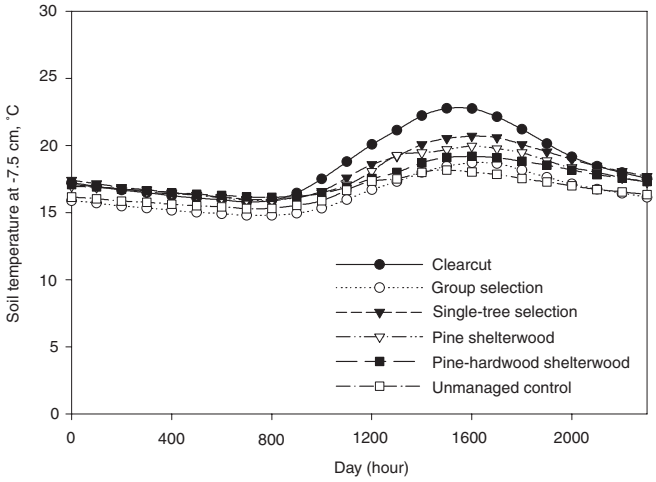

Figure 3—Mean hourly soil temperature at a depth of 7.5 cm by treatment.

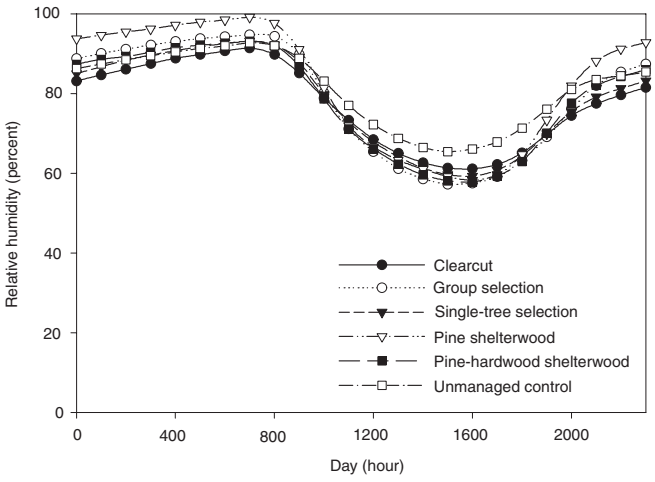

Figure 4—Mean hourly relative humidity by treatment.

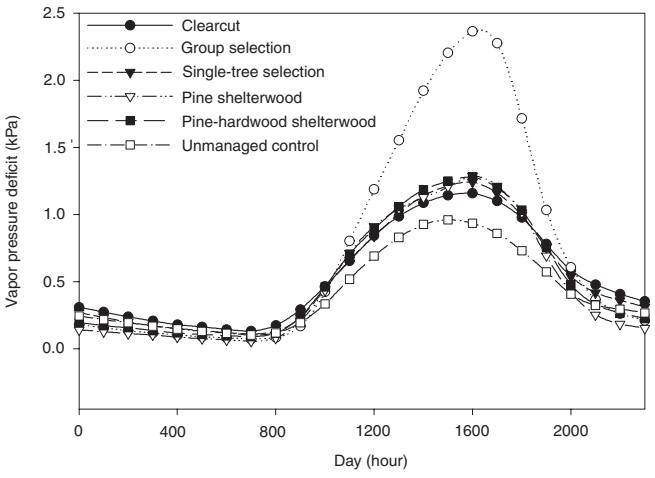

Figure 5—Mean hourly vapor pressure deficit by treatment.

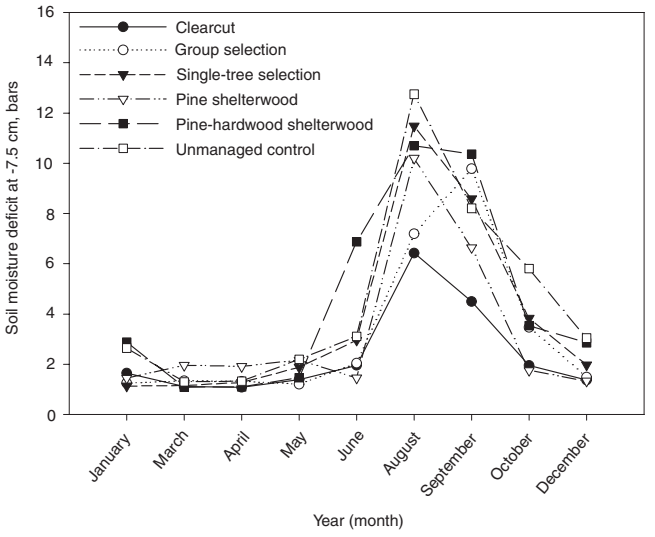

Figure 6—Mean monthly soil moisture deficit at a depth of 7.5 cm by treatment.

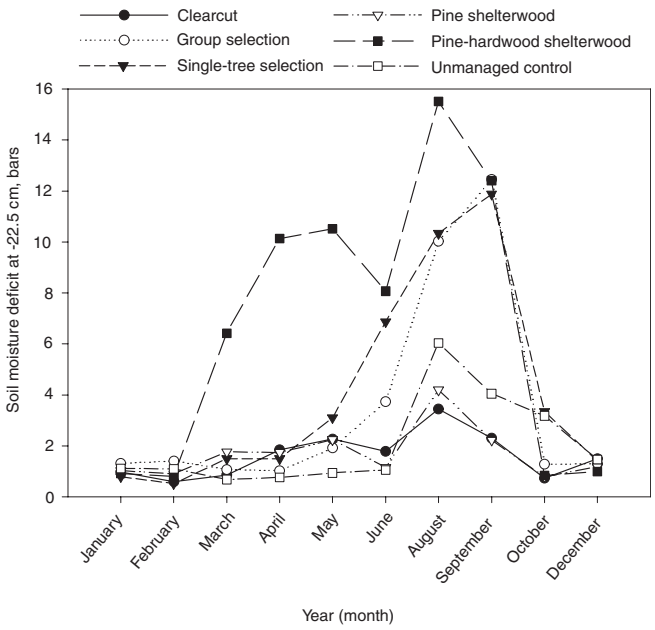

Figure 7—Mean monthly soil moisture deficit at a depth of 22.5 cm by treatment.

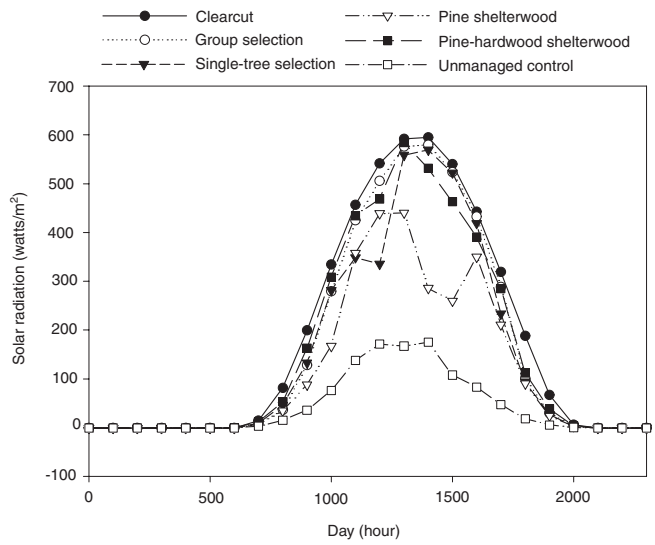

Figure 8—Mean hourly solar radiation by treatment.

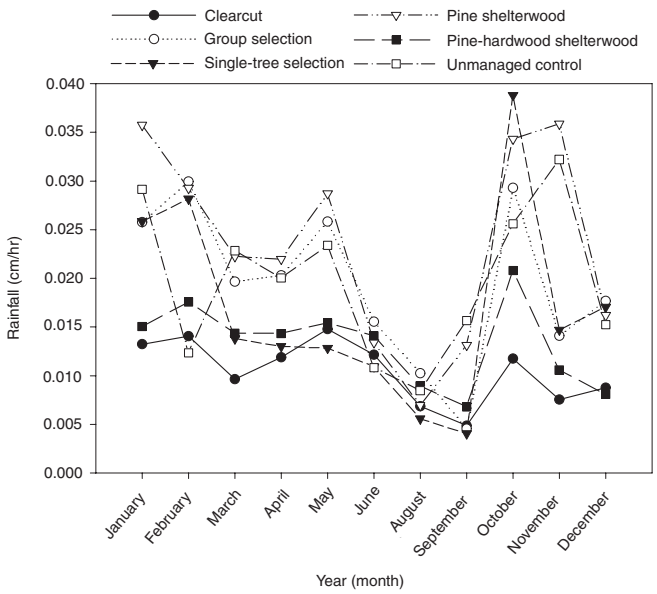

Figure 9—Mean monthly rainfall by treatment.

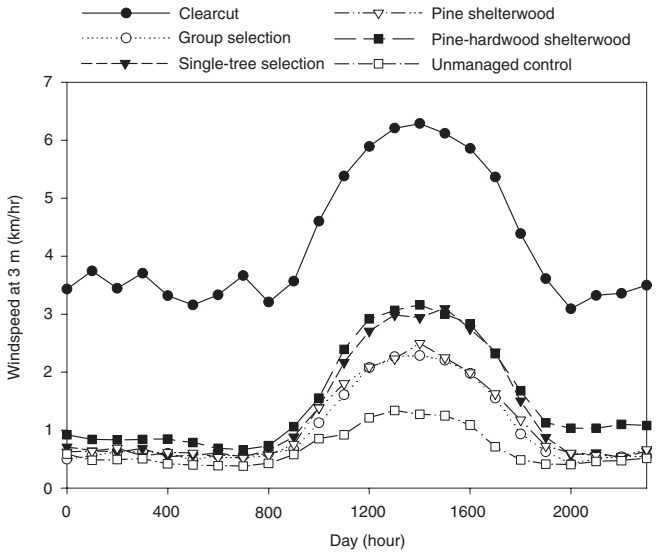

Figure 10—Mean hourly windspeed at 3 m aboveground by treatment.

2000 hours p.m., with a peak at roughly 1400 hours (fig. 10). The differences between the clearcut and the other treatments are such that the nighttime values for the clearcut treatment are roughly equal to the highest afternoon values for the other treatments, and the mean windspeed for the clearcut at its maximum is greater than 6 km/hour.

DISCUSSION

A ranking of the mean differences among variables by treatment suggests that the microclimatic effects associated with different reproduction cutting methods vary considerably in magnitude. Variables for which the greatest treatment mean is more than double that of the least are windspeed, solar radiation, and the soil moisture block at 22.5-cm depth (5.26, 3.23, and 2.64 times greater, respectively). Variables for which the difference between greatest and least treatment means is < 20 percent include the air temperature at 2 m, soil temperature, air temperature at 15 cm, and relative humidity (14, 13, 10, and 6 percent, respectively.) The management of shade has been cited as a key element in reproduction cutting methods that rely upon natural regeneration (Baker and others 1996); these results suggest that it is certainly among the most noticeable effects.

When comparing the microclimatic conditions of a clearcut vs. a group selection opening, results suggest that there are important differences. The clearcut is more fully open

and exposed than the group selection, as judged by higher means for the solar radiation, windspeed, soil temperature, and air temperature at 15-cm variables. Though temperatures are higher in the clearcut in the microclimatic zone immediately above and below the soil surface, the windspeed suggests that turbulent flow helps promote convective heat dissipation, and as a result, seedlings would not be subject to VPDs as high as those reported for the group selection. Prescriptions that call for the use of group selection as a substitute for clearcuts must be made with the acknowledgment that there will be important microclimatic differences between the two treatments.

Something unusual is occurring in the group selection openings. The data for the air temperature at 2 m in the group selection appears to be more than an instrumentation problem, because the air temperature sensor in the group selection treatment was repeatedly checked and was replaced during the course of the study. The most obvious possibility is the existence of a localized thermal inversion within the group opening, the effect of which is increased due to the lack of airflow. More work is needed to better establish and characterize the existence of this phenomenon in group openings.

Data do not point to a clearly discernible microclimatic effect in the retention of a hardwood component in the shelterwood treatments. The major differences between treatments are the higher means for the relative humidity in the pine shelterwood and the higher means for the two SMD and VPD variables in the pine-hardwood shelterwood. That may point to an influence in the hardwood component reducing soil moisture and subjecting the stand to a higher moisture stress from transpirational water loss. However, any such influence is far from convincingly demonstrated. For those variables where one might expect the pine shelterwood to have higher means than the pine-hardwood shelterwood, such as solar radiation and windspeed, the opposite was observed.

Finally, most of the microclimatic differences between the single-tree selection and the unmanaged control were minimal. The unmanaged control had higher relative humidity, lower VPD, lower windspeed, and lower soil temperature than the single-tree selection, though most of those variable means were not the highest or lowest across all treatments in the study. The one microclimatic difference of tremendous importance between the unmanaged control and the single-tree selection, and in fact between the unmanaged control and all other treatments, was the mean for the solar radiation variable. The unmanaged control had the lowest solar radiation of all treatments, and more than three times lower than the single-tree selection treatment. This points to the major difference between the unmanaged control and the single-tree selection: when prescribing the latter, enough cutting must be done to allow sunlight to reach the forest floor at levels high enough to support seedling establishment and survival. Solar radiation levels and means for other microclimatic variables in the study might be sufficient in the unmanaged control treatment to support seedling establishment, but levels of photosynthesis required to support acceptable height growth of pine seedlings in that treatment are not likely to be achieved. That in itself is the most important microclimatic difference between the unmanaged control and the single-tree selection treatments.

Further work is needed to develop an analytical process that allows one to compare variables when one or more stations are offline. The requirement that data be included in this study only during concurrent station operations led to the exclusion of a majority of the observations. Analysis of those data under a better process could produce a more robust quantitative comparison, by promoting annual, monthly, or hourly comparisons over time. In addition, unpublished data exist that measure seedling growth during this study; further work is needed to relate seedling growth to these microclimatic variables.

ACKNOWLEDGMENTS

Thanks to former Southern Research Station employees John McGilvray, who installed and repaired the stations, and Leif Anderson, who conducted monthly visits. Thanks also to Tim Martin of the University of Florida, who gave valuable advice on the calculation of the VPD variable.

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AN ASSESSMENT OF MISSISSIPPI´S NONINDUSTRIAL PRIVATE FOREST LANDOWNERS' KNOWLEDGE OF FORESTRY BEST MANAGEMENT PRACTICES

Andrew James Londo and John Benkert Auel[1]

Abstract—This study examined the knowledge levels of Mississippi nonindustrial private forest (NIPF) landowners relative to best management practices (BMPs) for water quality. Data were collected through surveys of participants in BMP programs held in conjunction with County Forestry Association (CFA) meetings throughout Mississippi during 2001-02. Ten CFAs participated in this study. Participants were asked several demographic and BMP-related questions prior to a presentation. Results showed that participants owned an average of 280 (n = 213) acres, whereas the average Mississippi NIPF landowner owns 50 acres (n = 360,000). Responses to BMP-related questions reveal that Mississippi NIPF landowners have a low level of knowledge concerning BMPs. This situation is likely similar to other States in the Southeastern United States. These results may overestimate the BMP knowledge level of forest landowners in Mississippi if it can be assumed that CFA members are more active and informed about managing their forest land. Improved educational programs for NIPF landowners, along with better communication between foresters, loggers, and NIPF landowners, is needed if BMPs are to be used effectively in Mississippi and across the Southeastern United States.

INTRODUCTION

The quality of water produced from forested watersheds is generally high (NCASI 1994). However, forest management activities have the potential to disturb the soil, which can lead to erosion and decreases in long-term site productivity and water quality (Aust and others 1998, Londo and Mroz 2001). Passage of the Water Quality Act of 1987 established that programs for the control of nonpoint sources of pollution be implemented by the States. Nonpoint sources have no specific point of entry into a watercourse and, as such, can not be defined. To reduce the impact of forest management activities on nonpoint source pollution, all States have developed a set of Forestry Best Management Practices (BMPs) in order to be in compliance with the Water Quality Act of 1987 (Lickwar and others 1990). BMPs can be defined as a collection of practices that limit the displacement of soil during and after forestry operations and maintain water quality (Shuler and Briggs 2000). Various studies have been conducted to determine the effectiveness of BMPs around the country (Adams 1998, Briggs and others 1998, Seyedbagheri 1996).

Educational programs have been conducted nationwide for loggers and foresters (Schaffer and Meade 1997), many in conjunction with the Sustainable Forestry Initiative (SFI). One of the main goals of SFI has been to educate foresters and loggers about the effects of forest management on water quality. Much less attention, however, has been given to educating nonindustrial private forest (NIPF) landowners about BMPs. This is especially problematic in the Southeastern United States where most of the forest land is owned by NIPF landowners (Arano and others 2002). NIPF landowners have control over practices and activities conducted on much of the productive forest land in the southern region. To ensure that water and site quality are protected on these land holdings, it is critical that landowners know about the importance and use of BMPs. This study was part of an NIPF BMP educational program held across Mississippi. In conjunction with the educational programs, NIPF participants were surveyed to determine their knowledge level of BMPs. The goal of this study was to quantify landowner characteristics and BMP knowledge levels. This information was then used to refine the educational programs provided in Mississippi. The study can also be used for developing similar programs across the southern region.

METHODS

BMP Surveys

Surveys (n = 313) were given to participants prior to BMP educational programs held across the State of Mississippi. Participants were members of County Forestry Associations (CFAs). CFAs were chosen because members are typically active in forest management, and they provide a ready audience for forestry education activities. Participants were asked a number of demographic questions including: age, gender, and the number of forested acres owned. These data were important for the characterization of participants so that comparisons could be made with other landowners in Mississippi.

The following BMP-related questions were asked:

1. What are BMPs?
2. Are BMPs voluntary in Mississippi?
3. What kind of pollution are BMPs designed to prevent?
4. What is a Streamside Management Zone (SMZ)?
5. Can you harvest within an SMZ?

Ten CFAs from across Mississippi participated in this study. One of the CFAs, the Tate/Desoto CFA was a combination of two counties. These CFAs were evenly distributed across the State to provide a representative sample. A map showing the location of participating counties can be found in figure 1.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

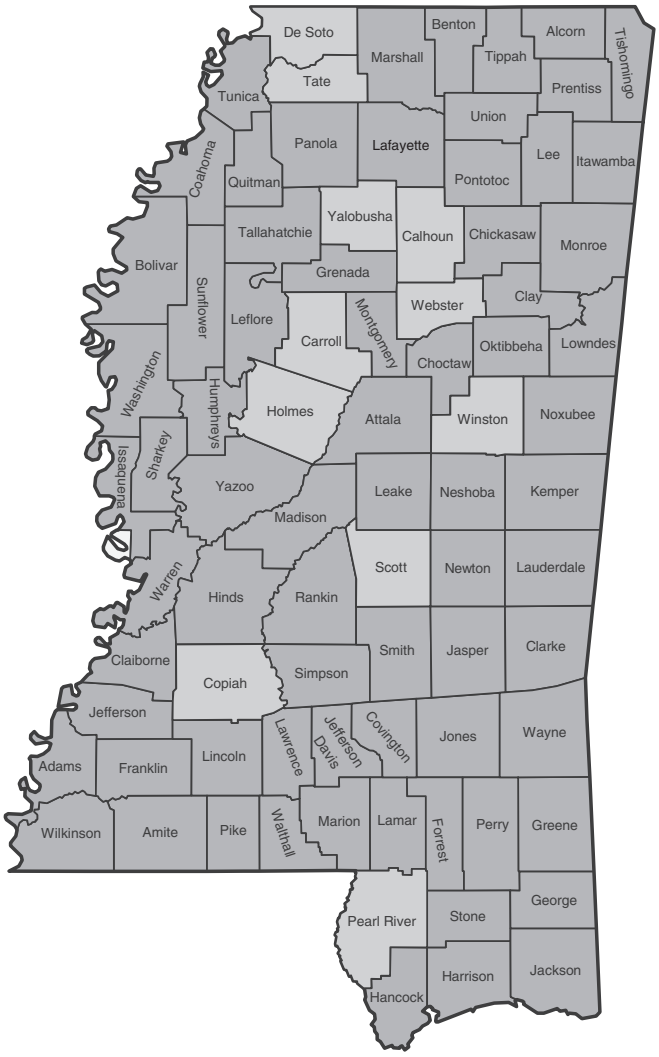

Figure 1—Locations of County Forestry Associations participating in the NIPF landowner BMP program in Mississippi.

All surveys were distributed prior to the presentation of a BMP educational program to ascertain participants' knowledge levels. The BMP program consisted of an hour-long presentation outlining the Mississippi forestry BMP guidelines. All program participants were provided copies of the Mississippi BMP guidelines as well other related publications. Attempts were made to distribute identical surveys at the end of each program; however, there was limited participation because most attendees departed without completing the second survey.

Data Analysis

Data were summarized by CFA, with overall statewide values presented. BMP questions were evaluated as either being correct, incorrect, or having no response. In most cases, 'textbook' answers were not provided by participants. However, answers were considered correct if participants had functional knowledge of what was being asked.

RESULTS AND DISCUSSION

Characteristics of Participants

There were a total of 213 participants in this study. A summary of participant characteristics can be found in table 1. Males comprised 82 percent (n = 175) of participants, owned an average of 294 acres of forest land, and averaged 51 years of age. Female participants comprised 18 percent (n = 38), owned an average of 214 acres, and averaged 61 years of age.

The large landholding size of participants may be somewhat misleading. There are approximately 386,000 landowners in Mississippi owning, on average, 50 acres (Londo 2000). It could be assumed that NIPF landowners with larger land holdings may be more interested and knowledgeable about forest management than those with smaller land holdings. This may also indicate why they are CFA members.

Table 1—Characteristics of participants in Mississippi NIPF best management practices education project acquired from surveys given in 2001–2002

Gender			Mean age	Mean acres owned (total acres)
	no.	*%*		
Male	175	(82)	51	294 (51,463)
Female	38	(18)	61	214 (8,118)
Total	213		53	280 (59,581[a])

[a] Approximately 0.5 percent of NIPF owned forest lands in Mississippi.

What Are BMPs?

Landowners were asked to define BMPs. Of the responses, 29 percent (n = 61) correctly defined what BMPs were, 28 percent (n = 60) provided incorrect responses, and 43 percent (n = 92) did not respond to the question (table 2). Many replies were given including: practices designed to increase forest productivity (n = 20), activities that maximize the good of the forest (n = 12), activities intended to improve wildlife habitat (n = 8), and rules that loggers follow to reduce water, air, and soil pollution (n = 1). The variety of responses illustrates part of the problem with BMPs and forest landowners: the term does not portray a clear idea about its meaning. The statement that BMPs "are rules that loggers follow to reduce water, air pollution" shows that there is miscommunication between the forest products industry and forest landowners. BMPs are important to all parties involved, not only the loggers. Landowners also need to realize that they are ultimately responsibile to ensure that BMPs are followed on their property.

Are BMPs Voluntary in Mississippi?

Participants were asked if BMPs were voluntary in Mississippi. Of the responses, 58 percent (n = 123) stated that BMPs are voluntary, 11 percent (n = 23) said they

Table 2—Responses to BMP questions by the 213 participants in the Mississippi NIPF best management practices education project acquired from surveys given in 2001-2002

Question	Yes	No	Did not answer
What are BMPs?	61	60	92
Are BMPs voluntary in Mississippi?	123	23	67
BMPs are designed to control what kind of pollution?	108	20	85
What are streamside management zones (SMZs)?	87	36	90
Can you harvest within an SMZ?	84	65	74

BMPs = best management practices.

were not voluntary, and 31 percent (n = 67) did not respond (table 2). Forestry BMPs in Mississippi are technically voluntary. During programs, many attendees expressed resistance to voluntary or compulsory compliance. NIPF landowners need to realize that whereas BMPs are technically voluntary, compliance with the State and Federal Water Quality Acts is mandatory, and the best way to be in compliance is to follow BMPs. The maintenance of water quality benefits everyone and supersedes individual landowner rights in many instances.

BMPs Are Designed to Reduce What Kind of Pollution?

Landowners were asked what kind of pollution BMPs were designed to reduce. Of the responses, 5 percent (n = 10) identified nonpoint source pollution and 46 percent (n = 98) identified water or soil pollution. Nine percent (n = 20) answered incorrectly, and 40 percent (n = 85) did not respond (table 2). Many alternative answers were given including no answer (n = 15), air pollution (n = 7), and the ozone layer (n = 1). The fact that so many replied that no pollution was generated by forestry operations puts the purpose and effectiveness of BMP implementation in question. Once again, landowners need more information and education concerning BMPs and their use. Foresters also have a responsibility to inform landowners about BMPs and their importance.

What Are Stream Side Management Zones (SMZs) and Can You Harvest Within Them?

Participants were asked to define SMZs. Of the responses, 41 percent (n = 87) identified an SMZ, 17 percent (n = 36) answered incorrectly, and 42 percent (n = 90) did not respond (table 2). When asked if harvesting was permitted within SMZs, 34 percent (n = 74) identified harvesting was permitted within SMZs, 32 percent (n = 65) answered incorrectly, and 34 percent (n = 74) did not respond. The number of incorrect replies and nonresponses is problematic.

An issue raised by several participants was the loss of productive timberland to the SMZ. For example, SMZs were found to remove 6.3 percent of forest land from productivity in Arkansas (Kluender and others 2000). Another concern raised about SMZs and BMPs in general are the implementation costs. Lickwar and others (1992) found that implementing BMPs cost an average of 2.9 percent of the timber sale revenue. In another study, Aust and others (1996) found that Virginia forest landowners pay much of the cost of implementing BMPs. Also, they concluded that much of the costs associated with BMPs are from opportunity costs associated with the loss of productive lands.

Whereas the costs of such activities will continue to be a problem, NIPF landowners need to be aware of the benefits of leaving the SMZ, including a reduction in sediment entering into water bodies, maintenance of stream temperature, and corridors for wildlife (Belt and O'Laughlin 1994, Harper 1978) and that those benefits extend far beyond their property boundaries.

CONCLUSIONS

NIPF landowners control approximately 12 million acres (62 percent) of the forest land in Mississippi (Londo 2000). They have great control over water-quality issues derived from forested lands. Grado and others (2002) reported that 67 percent of Mississippi NIPF landowners associated with CFAs were familiar with BMPs. The data presented here are much lower (table 2). Reasons for this discrepancy may include a smaller sample size and different study methodologies. Both studies, however, show the need for more education of NIPF landowners concerning BMPs and water-quality issues.

Increased BMP educational opportunities need to be directed towards NIPF landowners in Mississippi and around the southern region. This can be accomplished through formal educational programs and by loggers and foresters communicating more clearly with the landowners on whose land they are working. NIPF landowners in Mississippi and across the southern region need to realize the importance and role of BMPs in forest management and water quality as well as their own responsibility in ensuring that BMPs are followed on their land.

ACKNOWLEDGMENTS

This project was made possible by a Section 319(H) grant obtained through the Mississippi Department of Environmental Quality. Georgia-Pacific Corp., Plum Creek Timber Co., and Weyerhaeuser Co. also provided support for this project. Drs. Laura Grace and Emily Schultz of the Department of Forestry at Mississippi State provided reviews of this manuscript. Approved for publication as Article No. FO 227 of the Forest and Wildlife Research Center, Mississippi State University.

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PRELIMINARY RESULTS OF DOUBLE-SAMPLE FOREST INVENTORY OF PINE AND MIXED STANDS WITH HIGH- AND LOW-DENSITY LIDAR

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Abstract—LiDAR data (0.5 and 1 m postings) were used in a double-sample forest inventory on the Lee Experimental Forest, Louisiana. Phase 2 plots were established with DGPS. Tree d.b.h. (> 4.5 inches) and two sample heights were measured on every 10th plot of the Phase 1 sample. Volume was computed for natural and planted pine and mixed hardwood species. LiDAR trees were selected with new algorithms and focal filter procedures and height computed as the z-difference between interpolated canopy and DEM surfaces. LiDAR-derived heights were regressed against ground estimates. D.b.h.-height and LiDAR ground-height models were used to predicted d.b.h. from adjusted Lidar height and compute ground and LiDAR estimates of basal area and cubic volume. Phase 2 LiDAR estimates in mixed stands were computed by randomly assigning heights to species classes using a Monte Carlo simulation. Regression coefficients for Phase 2 estimates of square foot and cubic foot volume were computed for combined species-product classes. Regression estimates for low-and high-density LiDAR combined volume were partitioned by species-product distribution of Phase 2 volume. There was no statistical difference between low- and high-density LiDAR estimates on the adjusted mean volume estimate (sampling errors of 10.41 percent and 11.75 percent).

INTRODUCTION

Light detection and ranging (LiDAR) is a new remote sensing tool that has the potential for use in the acquisition of measurement data for inventories of standing timber. LiDAR systems have been used in a variety of forestry applications (Lefsky and others 1999, Means and others 1999, Nelson and others 1988, Nilsson 1996) for the quantification of biomass, basal area, and tree-and stand-height estimates. Means and others (2000) used LiDAR to predict forest stand characteristics and suggested that LiDAR was a promising method for use in forest sampling because it allowed adequate measurement of structural attributes of a timber stand. Height estimations by Magnussen and Boudewyn (1998), Young (2000), and Harrington (2001) reported underestimates of 1 to 4 m. McCombs and others (in press) have developed algorithms and focal filter procedures to determine tree location and estimate tree height, and Collins (2003) is working on draping multi-spectral imagery over LiDAR canopy surface models for hardwood species identification. The objectives of this study were to investigate the use of LiDAR in forest inventory of pine and mixed stands and to test protocols for using LiDAR in a double-sample inventory procedure.

STUDY AREA

The study area (1,200 acres) was located on the Louisiana State University, Lee Experimental Forest near Bogalusa in Washington Parish, LA. Forests within this region are dominated by natural and planted stands of loblolly pine (*Pinus taeda*), natural shortleaf pine (*P. echinata*), and mixed hardwood stands of red oaks (*Quercus* spp.), sweetgum (*Liquidambar styraciflua*), and hickory (*Carya* spp.). The cooperative project with LSU was funded by the Mississippi State University Remote Sensing Technology Center (MSU-RSTC), and NASA Stennis Space Center.

METHODS

LiDAR Procedures

Airborne 1 acquired the small-footprint, multi-return LiDAR data of the study area in June 2002, with an Optech ALTM-1225 system to attain nominal posting densities of 1 m (one hit per m^2, footprint size of 0.213 m) and 0.5 m (four hits per m^{2-}, footprint of 0.122 m) for up to five returns. The low-density data were obtained at an altitude of 1,067 m on a swath width of 609 m and the high-density data from 610 m on a 189- m swath. Each return consisted of a UTM (Zone 15, NAD 83) x, y, and z coordinate, where z was height above ellipsoid (HAE) in m. The LiDAR data sets were surfaced to produce first return canopy and last return digital elevation models (DEM) with 0.2 m- cell sizes using a linear interpolation technique. Tree locations and heights were determined with algorithms and focal filter procedures developed by McCombs and others (in press) that use a "variable search window radius based on relative density". These procedures use moving, simultaneous 2.5-, 4.0-, and 5.5-foot-radius search windows that choose tree height as the point that is higher than 85 percent of the surrounding maxima from one of the three search windows. Tree height was interpreted as the difference between canopy and DEM z-values at each tree location. Tree heights were converted to point coverages and clipped to sample-area boundaries using UTM coordinates to describe sample plot locations and sizes.

Inventory Design

The inventory design for this double-sample application involved the use of a series of circular plots 0.05 acre in size. One hundred and forty-one (141) Phase 2 and 1,410 Phase 1 plots were established within the study area. Every 10th plot was a Phase 2 ground plot with other plots being Phase 1 LiDAR plots (fig. 1). UTM coordinates were established at the center of each Phase 2 plot for navi-

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

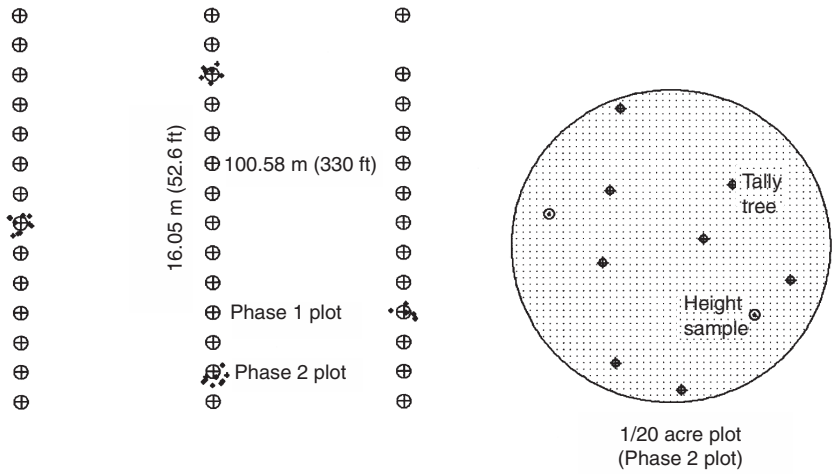

Figure 1—Plot and line design for Phase 1 LiDAR and Phase 2 ground (0.05 ac) plots for double-sample inventory of Lee Forest, Louisiana.

gation with real-time Differential Global Positioning System (DGPS). Differential corrections were obtained satisfactorily under the tree canopies by using a large dome antenna.

Ground data on Phase 2 plots included tree diameter at breast height (d.b.h.) on all trees > 5.5 inches in d.b.h. on the plot and total height on the two sample trees with minimum and maximum encountered d.b.h. and a crown class of dominant, co-dominant or intermediate. Ground data collection was completed for 141 Phase 2 plots in 2002, but LiDAR interpolations were completed for only 58 Phase 2 and 629 Phase 1 plots prior to this presentation. Thus, the preliminary results presented in this paper represent less than half of the study area and may not be indicative of the complete data set.

Double-Sample, Regression Estimator Model

The double-sample model widely used with ground-based point sampling (Avery and Burkhart 2002) and aerial photogrammetric inventories and adapted for this study was:

$$\overline{Y}_{lr} = \overline{y}_2 + \beta(\overline{X}_1 \ \overline{x}_2) \quad (1)$$

With traditional aerial photogrammetric inventories, the X_{1i} and x_{2i} variables are photo volume per acre and ground volume per acre from the Phase 1 and the Phase 2 plots, respectively, and β is the regression slope coefficient for y_i (ground volume per acre) over x_{2i} (LiDAR volume per acre on ground plot).

LiDAR is a new remote sensing tool that provides relatively precise measures of x-y-z UTM coordinates that can be surfaced and interpolated to produce estimates of heights and numbers of trees. Since there is only digital data, any estimate of basal area and volume must be derived from the height estimates as predictors of d.b.h. In this study, Phase 2 tree measures of d.b.h. and height were used to derive LiDAR estimates of basal area (square feet) and volume (cubic feet) by using d.b.h.-height equations to predict d.b.h. and basal area, and using the d.b.h. and height in a standard, standing-tree volume equation to predict volume (cubic feet). Thus, the double-sample models used in this study involved LiDAR mean estimates of basal area (LiBA) and volume (LiVOL) for the x-variables as:

$$\overline{Y}_{lr} = \overline{y} + \beta(LiBA - liba) \quad (2)$$

$$\overline{Y}_{lr} = \overline{y} + \beta(LiVOL - livol) \quad (3)$$

DATA ANALYSIS

The per-acre number of trees, basal area, and volumes for 58 Phase 2 ground plots and total heights of trees for 629 Phase 1 low-density LiDAR plots and 611 high- density LiDAR plots were computed and stored by plot number in text-data format for subsequent use in a spread sheet and custom software.

Phase 1 Plots

LiDAR height was adjusted to ground height for high-and low-density LiDAR estimates with the combined species models:

High-Density LiDAR: $H_{h,gr} = 2.4716 + 0.9788\ H_{h,Li}$ (I^2 =89.9) (4)

Low-Density LiDAR: $H_{l,gr} = 2.9930 + 0.9758\ H_{l,Li}$ (I^2 =87.7) (5)

where $H_{h,Li}$ is estimated height with high-density LiDAR, $H_{l,Li}$ is estimated height with low-density LiDAR, $H_{h,gr}$ is measured ground height of trees on high-density LiDAR plots, $H_{l,gr}$ is measured ground height on low density LiDAR plots, and I^2 is the statistical index of fit. D.b.h. and height from the ground plots were fitted to the combined species, d.b.h.-height model:

$$\text{d.b.h.} = 2.3930 + 0.000179\ [\text{Ln}(H_{gr})]^{7.4808} \quad (I^2 = 76.1) \quad (6)$$

where H_{gr} is ground height of measured trees.

Phase 2 Plots

LiDAR height was adjusted to ground height for high- and low-density LiDAR estimates with the following pine and hardwood models:

High - Pine: $H_{h,gr} = 3.8390 + 0.9689\ H_{h,Li}$ (I^2 =90.2) (7)

Low - Pine: $H_{l,gr} = 3.2505 + 0.9792\ H_{l,Li}$ (I^2 =88.0) (8)

High- Hardwood: $H_{l,gr} = 5.2776 + 0.8909\ H_{l,Li}$ (I^2 =78.2) (9)

Low - Hardwood: $H_{l,gr} = 8.3140 + 0.8392\ H_{l,Li}$ (I^2 =78.6) (10)

Tree d.b.h. was computed with the ground height models for pine and hardwood:

Pine: $d.b.h._{pine} = 1.1032 + 0.00064771[Ln(H_{gr})]^{6.6747}$ (I^2 =78.7) (11)

Hardwood: $d.b.h._{hdwd} = 2.8956 + 0.00006391[Ln(H_{gr})]^{8.2591}$ (I^2 =72.5) (12)

LiDAR Basal Area and Volume on Phase 2 Plots

Basal area and volume on the Phase 2 LiDAR plots were obtained by randomly assigning the LiDAR-derived tree heights to species percent distribution classes on each plot with a 500-iteration Monte Carlo simulation. Prior to the simulation, percent distribution by species-product class on each Phase 2 plot was ordered from largest to smallest. At each iteration, a new seed was selected from the time clock, and the randomly selected heights were randomly allocated to a species-product class. Once allocated to species-product class, the random LiDAR height was adjusted to ground height with equations (7) through (10) depending on species, and high-or low- density LiDAR and ground height were used to predict tree d.b.h. with equations (11) or (12), calculate basal area, and predict cubic foot volume with a standing tree volume equation. Average heights, basal areas, and volumes by species-product class for each ground plot for the 500 iterations were saved in text data format for subsequent combination with other plot data.

LiDAR Basal Area and Volume on Phase 1 Plots

Basal area and volume on the Phase 1 LiDAR plots were obtained by adjusting the LiDAR heights with equation (4) or (5), predicting d.b.h. with equation (6), and calculating basal area and volume. Assignments to species-product classes were not made on individual Phase 1 plots. Species-product volumes were subsequently obtained on the Phase 2 plots by partitioning the combined volume estimate into the respective species-product classes.

RESULTS

LiDAR vs Ground Height

The differences between ground measured and LiDAR estimates of height were significant (at $\alpha = 0.05$). High-density LiDAR heights had a bias of approximately -2.5 feet (equation 4), whereas low-density LiDAR heights had a bias of approximately -3.0 feet (equation 5). Height bias will result in differences in volume, but the volume differences can be “adjusted” with either the ground-LIDAR height equation prior to volume computation or with the regression estimator in the double-sample model if unadjusted heights are used to compute tree volume.

LiDAR heights are generally underestimated because the probability of a laser return from the terminal of conical-shaped crowns is very low. The narrower and more conical the crown, the greater the likelihood that the pulse return is from a portion of the crown below the terminal. It appears that heights from high-density LiDAR more closely approximated ground-measured heights than did heights from low-density LiDAR.

Phase 1 Relationships and Values

On Phase 1 plots, the composite species ground-LiDAR height and d.b.h.-height relationships were used to obtain combined per-acre estimates of trees, basal area, and cubic foot volume (table 1). The preliminary data suggests that low-density LiDAR produced higher estimates of numbers of trees than did high-density LiDAR or ground, thus resulting in higher estimates of basal area and cubic volume. These results were obtained with less than half of the Phase 1 and 2 plots.

Phase 2 Relationships and Values

Phase 2 ground and LiDAR volumes and basal areas for each species-product class are shown in table 2. The LiDAR volumes and basal areas for individual species-product classes were derived from the 500-iteration Monte Carlo allocation of heights. The random assignment of heights to species-product classes reasonably approxi-

Table 1—Phase 1 and 2 combined species, inventory results for per acre estimates of number of trees, basal area, and cubic foot volume from 629 high and 611 low density LiDAR plots (0.05 acre) vs. ground estimates from 58 plots on the Lee Experimental Forest, LA

Phase	Species	Product	High density LiDAR			Low density LiDAR		
			no.	*BA*	*ft³*	*no.*	*BA*	*ft³*
Phase 1 LiDAR	Combined	Combined	155	131	4,754	163	154	5,680
Phase 2 LiDAR	Combined	Combined	139	154	5,396	164	187	6,585
Phase 2 Ground	Combined	Combined	119	95	3,148			

LiDAR = light detection and ranging.

Table 2—Phase 2 inventory results for per-acre estimates of number of trees, basal area, and cubic foot volume from fifty eight–0.05 acre ground and high and low density LiDAR plots on the Lee Experimental Forest, LA

Species	Product	Ground			High density LiDAR			Low density LiDAR		
		no.	*BA*	*ft³*	*no.*	*BA*	*ft³*	*no.*	*BA*	*ft³*
Pine	Pulpwood	17	4	102	18	15	452	17	14	432
	Chip'n Saw	19	11	319	35	441	583	50	61	2,177
	Sawtimber	36	57	2196	33	48	1,724	48	70	2,486
Hardwood	Pulpwood	40	13	262	35	32	1,120	30	24	836
	Sawtimber	8	10	269	18	15	517	19	18	654
Combined	Combined	119	95	3148	139	154	5,396	164	187	6,585

LiDAR = light detection and ranging.

mated the actual ground distribution of volume and basal area, but it is apparent that LiDAR tended to overestimate numbers of trees per acre as compared to ground estimates. Overestimation of trees per acre resulted in overestimates of basal area and volume.

The regression relationships between ground and LiDAR basal area and volume were obtained from the Phase 2 data for combined species-product classes (table 3). LiDAR volume had a stronger relationship to ground volume than did LiDAR basal area, and low-density LiDAR relationships were stronger than high-density relationships.

Composite Species Double-Sample Estimates

Using double-sample model (3), the adjusted regression estimates of mean volume per acre and associated precision statistics for combined species-product classes with low- and high-density LiDAR are:

Low-Density LiDAR

$\overline{Y}_{lr}$ = 3,148 + 0.2373 (5,680 - 6,585) (13)

= 2,933 cubic feet per acre
(adjusted regression estimate of volume per acre)

$S_{\overline{Y}_{lr}}$ = ± 156 cubic feet (14)
(standard error of regression estimate)

S.E.= ±10.41 percent (15)
(sampling error @ 95 percent CL)

Table 3—Regression relationships and indices of fit for ground volume as a linear function of high and low density LiDAR volume per acre and basal area per acre for combined species on the Lee Experimental Forest, LA

Ground volume versus	β estimate	I^2
High density LiDAR volume	0.2561	39.5
Low density LiDAR volume	0.2373	54.3
High density LiDAR basal area	10.2209	37.0
Low density LiDAR basal area	9.2671	53.6

LiDAR = light detection and ranging.

High-Density LiDAR

$\overline{Y}_{lr}$ = 3,148 + 0.2561 (4,754 - 5,396) (16)

= 2,983 cubic feet per acre
(adjusted regression estimate of volume per acre)

$S_{\overline{Y}_{lr}}$ = ± 179 cubic feet (17)
(standard error of regression estimate)

S.E.= ± 11.75 percent (18)
(sampling error @ 95 percent CL)

The double-sample estimate of adjusted mean volume per acre, linear regression, using low-density LiDAR volume was 2,933 cubic feet with a standard error of 156 cubic feet and 2,983 cubic feet with a 179 cubic foot standard error for high-density LiDAR. The 95 percent confidence interval ($\alpha = 0.05$) about each estimate overlaps the other estimate, so there is likely no statistical difference between the two values. It appears that the low-density LiDAR estimate resulted in a lower sampling error than did the high-density LiDAR estimate. Since these estimates are based on 58 of 141 Phase 2 plots and 629/611 of 1,410 Phase 1 plots, statistically valid comparisons can not be made at this time.

Partitioning of Double-Sample Composite Estimate

The double-sample volume estimate for combined species-product classes using low- and high-density LiDAR volume produced estimates of 2,933 cubic feet per acre and 2,983 cubic feet per acre, respectively. Since it is somewhat tedious to do a Monte Carlo simulation to randomly allocate LiDAR heights to species-product classes at the Phase 1 level, the partitioning of a composite species estimate into the various species-product classes using the Phase 2 plot distributions might be a reasonable alternative. The partitioning of the composite volume estimates from the LiDAR volume approach using percent distribution of volume is shown in table 4. Parker and Evans (in press) previously reported no difference between partitioning the composite double-sample volume estimate by percent occurrence of trees, volume, or basal area on the Phase 2 ground plots into individual species-class volumes and obtaining individual species estimates with their respective double-sample equations.

Table 4—Distribution of combined regression estimates of mean volume per acre from low and high density LiDAR by percent-volume distribution within species-product classes on Phase 2 plots of double-sample inventory area of the Lee Experimental Forest, LA

Species	Product	Distribution	Low	High
		percent	- - - - - ft^3 - - - - -	
Pine	Pulpwood	3.24	95	97
	Chip n' saw	10.14	297	303
	Sawtimber	69.75	2,046	2,081
Subtotal		83.14	2,438	2,480
Hardwood	Pulpwood	8.31	244	248
	Sawtimber	8.55	251	25
Subtotal		16.86	495	503
Total		100.00	2,933	2,983

DISCUSSION

The double-sample regression estimates using LiDAR volume appeared to give reasonable volume estimates using the combined species-product approach even though less than half the data were analyzed. Precision statistics from the inventory provided reasonable validation data; however, these partial-sample results are inconclusive because of inadequate distribution of sample plots. Low-density LiDAR appeared best for estimating tree heights perhaps due to less bias and overall "noise". No statistical difference in numbers of trees between ground and LiDAR estimates was detected.

In single species stands, the problem of distributing heights and partitioning volume or basal area to species would not be present. In multiple species stands, the use of LiDAR basal area or volume in predicting double-sample estimates of volume should be investigated because either variable might be superior to the other. Parker and Evans (in press) found LiDAR basal area to be better than LiDAR volume in the Idaho study. However, the LiDAR posting spacing (2 m) was much lower on the Idaho site than it was on the Louisiana site (1 m and 0.5 m).

The combined species-product approach followed by distribution of resulting volume to individual species-product classes based on percent distribution of volume or basal area should yield similar results to the individual species approach. Procedures developed by Parker and Evans (in press) to randomly allocate the LiDAR heights to species-product classes in a Monte Carlo simulation worked reasonably well in this study. However, these procedures are being enhanced for subsequent analysis of the complete data set to allow allocation of Phase 2 LiDAR heights in a two-stage process—first to species class, then to product class with a check of d.b.h. merchantability limits.

LiDAR shows promise for forest inventory because it has the precision necessary to produce reliable estimates of trees per acre and standing tree height. Since d.b.h. is strongly related to height and stem density, reliable standing tree-volume estimates from LiDAR can be used effectively and efficiently in a double-sample design with traditional ground sampling methods to achieve inventory results at desired levels of precision. Biases in LiDAR heights and resulting basal areas or volumes or both are "adjusted" by the regression estimator in a double-sample model.

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SIZE OF COARSE WOODY DEBRIS 5 YEARS AFTER GIRDLING AND REMOVAL TREATMENTS IN 50-YEAR-OLD LOBLOLLY PINE PLANTATIONS

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Abstract—In 1996, a study began at Savannah River Site to investigate large-scale replicated forest areas to control coarse woody debris for integrated biodiversity objectives. Research design was a randomized complete block with four treatments replicated in four blocks, resulting in 16 plots. The treatments applied to 50-year-old loblolly pine stands were (1) control, (2) girdling of 25 percent of trees to create catastrophic simulation, (3) annual removal of down woody debris > 10 cm in diameter, and (4) annual removal of both standing and down woody debris > 10 cm in diameter. The study tracks coarse woody debris recruitment and loading, rates of decomposition, and effects on the forest ecosystem.

INTRODUCTION

The logs and snags in a forest, coarse woody debris (CWD), provide habitat, food, refuge, and nesting sites for many organisms across trophic levels (Harlow and Guynn 1983, Harmon and others 1986, Maser and others 1979, McComb and others 1986). Research studies have found that many organisms rely on CWD for all or part of their survival. CWD research is limited in the Southeast to studies focused on only a few organisms (Harlow and Guynn 1983, McComb and others 1986, McMinn and Crossley 1996). Forest management has become more intensive over the last century, and as a consequence, extensive CWD has been removed from the southern forest. Foresters need to understand how CWD maintains biodiversity and how management practices provide desired levels of CWD. The objective of this study is to establish large-scale replicated forest areas to control CWD to understand its characteristics and dynamics. This study will clarify the relative influence CWD exerts on faunal communities of the managed southeastern pine forest ecosystem. This research will track CWD recruitment and loading, rates of decomposition, and the effects of CWD presence and abundance on the forest ecosystem.

PROCEDURES

The study design is a randomized complete block design with 4 treatments replicated in 4 blocks, yielding 16 plots. Treatments were applied in 1996 and annually thereafter to 9-ha plots within loblolly pine (*Pinus taeda* L.) plantations that were established between 1950 and 1953:

(1) Control (CON) does not manipulate CWD, but allows natural dynamics
(2) Catastrophic simulation (CAT) will be a control for a baseline period, then create a snag pulse by girdling 25 percent of the living trees in the year 2001
(3) Down removal (DOW) removes the down woody debris > 10 cm in diameter to adjoining log decks annually and burns it while the standing woody debris is left remaining; in 2001, this treatment will fell 25 percent of the living trees to create a log pulse, and no removal will occur
(4) All removal (ALL) removes all woody debris > 10 cm in diameter, including snags, to adjoining log decks annually and burns it.

All previous CWD was removed from the study areas, and plots received herbicide spraying in 1996 to reduce vegetative cover variation. Plot 5 received yearly herbicide spraying to keep kudzu (*Pueraria lobata*) under control until 2001. The plots were prescribed-burned in February and March 2000, except for the four plots in compartment 54, which were burned in March 2001. Phase 2 of the project was implemented in 2001 on the CAT and DOW treatments. The CAT plots have had a quarter of the living trees' basal area girdled and injected with herbicide to create standing woody debris. DOW plots had the same amount felled to create downed woody debris. The CON and ALL plots were thinned by the same amount of basal area as the woody debris creation plots in order to keep light regimens the same. This paper includes pretreatment data from 1997 to 2001 before the 2001 treatments/ thinning were conducted. The selected trees in the CAT treatment were girdled before the 2001 inventory, but this report does not include their data. Decay classes refer to the amount of wood decay, not bark or standing integrity (Sabin 1991).

Studies

All compartments were used in data calculations and analysis. Plot summary tables and/or raw data are presented for each year. Means were determined for diameter/diameter at breast height (d.b.h.), length/height, and decay. Total number in each categorical data class was determined by year. All density, basal area, and volume values were calculated on a per-ha basis. Volume was computed for logs and snags < 2 m tall using Huber's formula: volume = cross-sectional area at log midpoint*length. Logs that were elliptical or flat were assumed to be 60 percent and 20 percent of the volume computed, respectively. For snags at least 2 m tall and trees, volume was computed by regional volume equations (Saucier and Clark 1985).

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

In order to determine any significant treatment andcompartment effects, analysis of variance (ANOVA) was performed. CON and CAT treatments were combined in the data reduction analysis, but not in the base analysis. Combining ALL and DOW treatments strengthened down-removal effects, and combining CON, CAT, and DOW treatments when looking at standing removal effects. Combined analyses are not reported unless there were significant differences for separate vs. combined treatments. If the *P*-value was < 0.0500, LSD tests were run to determine significant differences between treatments or compartments. Paired t-tests determined any differences between years. Chi-square analysis determined differences in categorical data between years or new pieces characteristics vs. removed pieces.

RESULTS AND DISCUSSION

Characteristics of CWD

A total of 3,789 pieces of CWD were tagged in 1997, 3,754 pieces in 1998, 3,756 pieces in 1999, 3,674 pieces in 2000, and 3,781 pieces in 2001, with 87 to 89 percent of the pieces down. Throughout the sampling period, most CWD stayed in the inventory without a change in inventory status (80 to 84 percent). Snags fell at a rate of 8 to 11 percent annually, especially increasing after the prescribed burns. The prescribed burns also consumed more snags and logs below the size limits for CWD than previous years (5 to 9 percent vs. 2 to 3 percent, respectively). Annually, only 2 to 3 percent of the existing logs and snags fragmented. The amount removed decreased over time, and all previous CWD was removed from the areas, including decayed logs.

In all years, pine constituted most of the pieces present, with oak (*Quercus* spp.) and black cherry (*Prunus serotina*) the next most abundant species. This composition reflected the living canopy, except that most of the black cherry stems were found dead in the plots.

Down Woody Debris

Length and diameter—Overall mean midpoint diameter increased over time from 15.4 cm in 1997 to 16.1 cm in 2001 as the logs decayed and their sides collapsed (table 1). The overall mean diameter increase was not significant ($P = 0.67$); the nonremoval plots significantly increased ($P = 0.01$). There were no significant differences at the 0.05 level between treatments or compartments for diameter. The overall mean length to a 10-cm diameter remained relatively static over time, ranging from 3.2 m in 1998 to 3.4 m in 2001 (table 1). There were no significant differences between treatments for length. Without much variation between years, in distribution most logs were small in diameter and short in length. Most of the smaller CWD were recruited after thinning in 1995 and 1996 and herbicide applications in 1996. Some of these logs are becoming too small to stay in the inventory; i.e., < 0.6 m in length or 10.0 cm in midpoint diameter, so the smaller size classes have reduced in number.

Additional characteristics—In 1997, 50 percent of the logs were assigned a decay class of 1 (sound), while only 20 percent were assigned decay class 3 (decayed). In 1998, 40 percent of the logs were class 1 logs, while

Table 1—Mean midpoint diameter, length, and decay for down woody debris by treatment and compartment for 1997 through 2001 for the Coarse Woody Debris Template Study in 50-year-old managed loblolly pine stands at the Savannah River Site, SC

	n					Diameter (*cm*)					Length (*m*)					Decay[a]				
	1997	1998	1999	2000	2001	1997	1998	1999	2000	2001	1997	1998	1999	2000	2001	1997	1998	1999	2000	2001
Treatment																				
CON	1,436	1,509	1,568	1,617	1,518	14.8	15.1	15.2	15.5	15.9	3.1	3.1	3.3	3.4	3.4	1.78 b[b]	1.83 c	1.89 a	1.90 a	2.01 a
CAT	1,493	1,582	1,653	1,522	1,661	15.4	15.5	15.6	15.9	16.2	3.5	3.4	3.3	3.3	3.4	1.53 c	1.60 d	1.72 ab	1.78 ab	1.93 a
DOW	268	134	43	56	131	17.5	19.4	17.2	18.2	17.4	3.3	2.2	2.8	3.9	4.2	1.79 b	2.06 b	1.20 b	1.18 c	1.39 b
ALL	178	100	9	15	14	16.5	18.2	12.8	17.2	13.2	3.7	3.4	2.4	3.3	2.1	1.95 a	2.34 a	1.39 ab	1.43 bc	1.07 b
P-value						0.3979	0.2640	0.2521	0.3336	0.0874	0.3611	0.1964	0.0894	0.7193	0.1500	0.0000	0.0000	0.0330	0.0100	0.0008
Compartment																				
15	876	877	792	769	803	15.6	15.6	15.4	15.7	16.0	3.3 ab	3.3 ab	3.3	3.1	3.3	1.86 b	1.86 b	1.92	1.93	2.04
30	856	857	841	822	810	13.9	14.1	13.7	14.4	14.5	3.1 b	3.0 b	3.0	3.1	3.2	1.33 d	1.43 d	1.51	1.61	1.78
54	621	613	624	641	708	17.5	17.4	17.5	17.7	18.1	4.3 a	4.0 a	4.5	4.5	4.4	2.18 a	2.18 a	2.05	2.03	2.02
55	1,022	978	1,016	978	1,003	15.5	15.6	15.6	16.0	16.1	2.9 b	2.8 b	2.9	3.0	3.0	1.52 c	1.66 c	1.77	1.80	1.95
P-value						0.0952	0.1484	0.4446	0.7387	0.6237	0.0412	0.0154	0.1284	0.2968	0.5789	0.0000	0.0000	0.3786	0.3776	0.1463
Overall	3,375	3,325	3,273	3,210	3,324	15.4	15.5	15.4	15.8	16.1	3.3	3.2	3.3	3.4	3.4	1.68	1.75	1.79	1.83	1.95

CON = control; CAT = catastrophic simulation; DOW = down removal; ALL = all removal.

[a] Decay classes were from 1 (sound) to 3 (decayed).

[b] LSD test run at significant difference of α = 0.0500. Means with the same letter were not significantly different from other treatments or compartments for that given year.

slightly decayed logs increased from 13 percent to 20 percent, whereas the other decay classes remained relatively static. In 1999, logs continued to decay, with decay class I and 1.5 logs each comprising 30 percent of logs present. The logs further decayed in 2000 and 2001, with only 20 percent and 13 percent of the logs remaining in decay class 1, respectively. In 2001, logs were significantly more decayed than the logs present in 1997 (P = 0.0000), with sound logs becoming increasingly decayed into the intermediate decay classes. Logs in the removal treatments have become less decayed than logs in the nonremoval treatments in 2001 (table 1). During the first two removals, very decayed pieces were left in place because they would easily dissociate upon lifting, but since the third removal these pieces were raked apart and thus taken out of the inventory.

In 2001, the typical log was without bark (44 percent), round (51 percent), either a main bole (41 percent), a top (33 percent), or an upturned bole (23 percent), and in full contact with the ground (59 percent). The amount of bark present decreased significantly since 1997 (P = 0.001), especially the presence of logs with 80 percent or more bark present. Logs have become less round in cross-sectional shape since 1997 (P = 0.001). Seventy percent of the logs in 1997 were round, while only 51 percent were round in 2001. More logs have at least 75 percent of the bole settled to the ground now than in 1997 (P = 0.000).

Each year had about the same amount of log fragmentation. Around 15 to 18 percent of the logs were associated with a base log, with an additional 2 to 4 percent associated with a snag still standing. For every log that was fragmented, there was an average of 1.7 associates. More pine logs had fragments than hardwood logs (20 percent vs. 12 percent). In 1998, 23 percent of the new logs fragmented from existing logs and 20 percent from snags still standing, while in 1999 only 11 percent of the new logs fragmented from existing logs and 33 percent from snags still standing. In 2000 and 2001, around 20 percent of the new logs fragmented from existing logs and around 25 percent from snags still standing. Furthermore, a quarter of the logs had human-caused mortality or fragmentation, as evidenced by at least one cut side, and an eighth of the logs were found in old log decks. Only 9 percent of the fragments had cut ends.

Cohort Changes

The 1997 cohort logs significantly increased in diameter and decreased in length since 1997 (P = 0.0045 and P = 0.0166, respectively) (table 2). As logs decay, they tend to lose structural integrity and thus become wider and more elliptical. The 1998, 1999, and 2000 cohorts also slightly increased in diameter, but their length stayed almost the same over time. The 1998, 1999, and 2000 cohorts were longer than the 1997 cohort, since the 1997 cohort

Table 2—Mean midpoint diameter, length, density, and volume for down and standing woody debris by cohort for 1997, 1998, 1999, 2000, and 2001 for nonremoval plots for the Coarse Woody Debris Template Study in 50-year-old managed loblolly pine stands at the Savannah River Site, SC

Inventory year	Down	Standing	Diameter		Length		Density		Volume	
	Down	Standing	Down	Standing	Down	Standing	Down	Standing	Down	Standing
	n		*cm*		*m*		*no./ha*		m^3/ha	
					1997 Cohort					
1997	2,929	376	15.1c[a]	21.6	3.3a	7.4	91.5a	7.8a	6.66a	2.12a
1998	2,900	320	15.3c	22.0	3.2b	7.3	90.6a	6.7b	6.35b	1.79b
1999	2,810	278	15.3c	22.4	3.1b	6.7	87.8a	5.8c	6.06c	1.40c
2000	2,579	214	15.7b	21.3	3.1b	6.6	80.6b	4.5d	5.69d	1.01d
2001	2,488	166	16.0a	20.2	3.1b	6.2	77.8c	2.5e	5.27e	0.64e
					1998 Cohort					
1998	191	76	15.7	19.3	4.1	6.9	6.0	1.6a	0.85	0.38a
1999	194	70	15.6	19.6	4.1	6.4	6.1	1.5a	0.86	0.32a
2000	183	54	15.9	19.0	4.2	6.3	5.7	1.1b	0.83	0.24a
2001	178	40	16.3	18.4	4.2	5.2	5.6	0.8c	0.78	0.13b
					1999 Cohort					
1999	217	116	16.2	23.9	4.8b	6.5	6.8	2.4a	1.24	0.75a
2000	209	104	16.5	25.0	4.9ab	6.3	6.5	2.1b	1.23	0.68a
2001	199	88	16.6	25.0	5.0a	5.9	6.2	1.8c	1.16	0.52b
					2000 Cohort					
2000	168	59	15.4	24.2	3.7	10.9	5.3	1.2a	0.59a	0.62
2001	166	52	15.5	25.1	3.6	11.0	5.2	1.1b	0.58b	0.56

[a] Paired t-tests run. Means with the same letter were not significantly different (α = 0.0500) from other inventory years for that given coarse woody debris type and cohort.

included many logs that have been onsite since before 1997. Over time, all cohorts have become significantly more decayed ($P = 0.0000$, $P = 0.0000$, $P = 0.0001$, and $P = 0.0027$ for 1997, 1998, 1999, and 2000 cohorts, respectively). The 1997 and 1998 cohorts have settled more to the ground ($P = 0.0000$ and $P = 0.0365$, respectively).

Standing Woody Debris

The overall mean d.b.h. ranged from 22.0 cm in 1999 to 20.9 in 2000 (table 3). In 1999 and 2000, the removal treatment d.b.h. was significantly less than the nonremovals. Otherwise, there were no significant differences between treatment or compartment for d.b.h. The overall mean height to a 10-cm-diameter top decreased from 7.3 m in 1997 to 6.5 m in 2001 (table 3). The nonremovals significantly decreased in height since 1997 ($P = 0.0423$). There were no significant differences between treatments for height, but there were significant differences between compartments for 1998 and 2000. Compartment 54 had significantly shorter snags than compartments 15 and 30. Without much temporal variation, most of the snags were small in d.b.h. and short in height, as is shown in their distributions, but there were several small peaks in the mid- to upper-size classes because of dead overstory pine. Other snag studies in southeastern pine forests have found snags clustered in the lower-size classes in the absence of catastrophic events (Carmichael and Guynn 1983, Harlow and Guynn 1983, McComb and others 1986). Snags are losing some height as tops of large snags fall. During the study period, snags collectively broke 28 to 32 times each year.

In 1997, 50 percent of the snags were assigned a wood decay class of 1, while < 10 percent were assigned decay classes 2.5 and 3. Snags probably fall before their wood has a chance to become very decayed since the removal treatment had less decayed snags (table 3) and snags that have fallen are not very decayed. Logs were more decayed than snags (tables 1 and 3). In 1998, some decay class 1 snags decayed slightly to become classified as decay class 1.5, whereas the other decay classes remained relatively static. In 1999, 2000, and 2001, there were more decay class 1 and 1.5 snags, mostly due to the fall 1998 windstorm damage and the prescribed burning consumption of decayed snags in 2000 and 2001. Decay classes refer to the amount of wood decay, not to bark or standing integrity, which other studies have incorporated into their decay classifications (Maser and others 1979, Raphael and Morrison 1987, Sabin 1991). Most snags had either little bark or a lot of bark. Logs had less in the upper bark presence classes than the snags.

In 2001, most snags had intact boles with at most the very top out (58 percent), though 41 percent had broken boles. Standing integrity changed between years mostly after disturbances. The percentage of snags that were broken increased in 1999 after the 1998 windstorm. In 2001, several trees died from fire, so the amount with intact boles with branches increased. Between 8 and 12 percent of the snags fell annually during the 4 years, while 6 to 15 percent broke part of their boles annually. The highest year of bole breakage was after the windstorm in 1999.

Table 3—Mean diameter at breast height, and decay present for standing woody debris by treatment and compartment for 1997 through 2001 for the Coarse Woody Debris Template Study in 50-year-old managed loblolly pine stands at the Savannah River Site, SC

	n					D.b.h.				Height				Decay[a]			
	1997	1998	1999	2000	2001	1997	1998	1999	2000	2001	1997	1998	1999	2000	2001	1997	1998	1999	2000	2001
						cm					m									
Treatment																				
CON	132	131	145	130	120	21.8	21.6	22.3 a[b]	21.5a	20.1	7.9	6.9	6.3	6.1	5.6	1.38	1.50a	1.41	1.29a	1.27
CAT	123	130	152	139	134	21.0	21.1	21.7 a	22.2a	21.6	7.4	7.2	6.6	7.2	6.7	1.37	1.36b	1.34	1.28a	1.26
DOW	121	135	167	162	180	22.1	21.9	23.0 a	23.1a	21.3	7.0	7.4	6.8	7.8	6.9	1.45	1.40ab	1.25	1.21a	1.22
ALL	38	33	19	33	23	21.1	15.0	13.5 b	15.4b	17.1	5.9	4.8	3.9	5.6	6.1	1.54	1.30b	1.08	1.03b	1.02
P-value						0.9877	0.3401	0.0077	0.0366	0.1978	0.7535	0.1933	0.0529	0.1060	0.5699	0.3661	0.0182	0.1934	0.0024	0.3039
Compartment																				
15	52	72	70	68	82	27.2	25.7	25.3	23.1	22.7	10.1	8.9a	8.6	10.0a	8.5	1.31	1.22b	1.24	1.14	1.18
30	45	59	62	45	58	23.6	22.3	22.9	24.0	19.5	9.3	7.6a	7.3	8.4ab	5.2	1.31	1.42a	1.33	1.16	1.14
54	188	187	218	224	178	19.3	18.3	21.8	21.7	21.4	6.1	5.6b	6.0	6.0c	6.2	1.44	1.45a	1.33	1.29	1.29
55	129	111	133	127	139	22.0	21.9	20.3	20.6	19.7	7.3	7.6a	5.8	6.7bc	6.1	1.44	1.47a	1.34	1.22	1.23
P-value						0.1175	0.0620	0.5596	0.7620	0.7446	0.1451	0.0056	0.7230	0.0156	0.4346	0.2910	0.0002	0.9610	0.1429	0.0925
Overall	414	429	483	464	457	21.6	21.0	22.0	21.8	20.9	7.3	7.0	6.5	7.0	6.5	1.41	1.41	1.32	1.24	1.24

D.b.h. = diameter at breast height; CON = control; CAT = catastrophic simulation; DOW = down removal; ALL = all removal.

[a] Decay classes were from 1 (sound) to 3 (decayed).

[b] LSD test run at significant difference of $\alpha = 0.0500$. Means with the same letter were not significantly different from other treatments or compartments for that given year.

For the vast majority of the snags, mortality causes could not be determined. The main cause of determinable mortality was wind, followed by fire (in 2001), suppression, insects, and lightning. In the fall of 1998, a windstorm blew down and broke several pines in some of the plots. Thus, wind-caused mortality increased in 1999. Over time, we might be able to determine how frequent wind mortality is in these loblolly pine forests. Suppression-caused mortality is increasing now and would increase over time without thinning. Fire seems to reduce the amount of snags by consuming all or part of them, but it also creates snags in the years following burning, although it tends to kill small hardwoods and consume large pine snags.

Over 80 percent of the snags had no cavities present. If cavities were present, most snags usually had only one or two. If wind is a major cause of death in these forests, snags may be broken or blown down before many are suitable for cavity establishment or shortly after cavities form. Also, most cavities are found in large-diameter and tall trees (Sabin 1991), and our plots do not have many large snags. More than 50 percent of our snags with cavities were > 25 cm d.b.h., especially snags with multiple cavities. Carmichael and Guynn (1983) found cavities in only 9 percent of the snags surveyed on the Clemson Experimental Forest in the upper Piedmont of South Carolina.

Determinable mortality varied by year, with wind mortality being highest in 1999 and suppression and fire mortality increasing in 2000 and 2001. Over all years, wind caused more snag generation than any other cause (29 percent). Lightning killed only 4 percent of the new snags, but insects killed one to several trees around the lightning-struck tree. In summary, when new snags originate in our stands, they are usually sound and have bark, intact boles, and no cavities. As snags are lost, they are somewhat decayed and have broken boles, and some have cavities.

The snags of each cohort year did not significantly change in d.b.h. or height over time, though the 1997 and 1998 cohorts did decrease over a m in height (table 2). Over time, the cohorts have become more decayed (significantly for the 1997 cohort, $P = 0.000$) and lost most branches on intact snags (significantly for the 1997 and 1998 cohorts, $P = 0.000$ and $P = 0.0028$, respectively). The 1997, 1998, and 1999 cohorts significantly increased in presence of cavities, but some were lost due to breakage ($P = 0.0047$, 0.0000, and 0.0008, respectively). After 2 to 3 years since recruitment, the 1998 and 1999 cohorts finally started having several snags with multiple cavities.

CWD Loadings

In 2001, nonremoval treatments had an average of 99 logs/ha, while removals had 1 log/ha (table 4). The DOW treatment did not receive the annual removal in 2001, so it increased from 3.5 to 8 logs/ha. Since 1997, the nonremovals increased in number, though they slightly decreased since 1999 because of consumption from fire, whereas the removals significantly decreased ($P = 0.0019$). The removal plots have 1 percent of the density of logs found on the nonremoval plots in 2003. There were no significant differences between compartments, although compartment 54 had the least amount. If snag-fall rates remained constant, 50 percent of the 1997 snags would be down within 3 to 4 years, which is what has happened (table 2). These agree with other snag-fall rates in southeastern forests (Dickson and others 1983, Sabin 1991), though snag-fall rates usually vary from year to year depending on environmental conditions (Harmon and others 1986).

Table 4—Down woody debris loading by treatment and compartment for 1997 through 2001 for the Coarse Woody Debris Template Study in 50-year-old managed loblolly pine stands at the Savannah River Site, SC

	Density					Volume				
	1997	1998	1999	2000	2001	1997	1998	1999	2000	2001
	- - - - - - - - - - - - - - - - - - - *no./ha* - - - - - - - - - - - - - - - - -					- - - - - - - - - - - - - - - *m^3/ha* - - - - - - - - - - - - - - -				
Treatment										
CON	89.8a[a]	94.3a	98.0a	95.1a	94.9a	5.53b	6.50a	7.88a	8.31a	8.18a
CAT	93.3a	98.9a	103.3a	101.1a	103.8a	7.79a	7.91a	8.45a	8.38a	8.76a
DOW	16.8b	8.4b	2.7b	3.5b	8.2b	1.36c	0.39b	0.24b	0.51b	1.21b
ALL	11.1b	6.3b	0.6b	0.9b	0.9b	0.63c	0.34b	0.01b	0.18b	0.03b
P-value	0.0006	0.0002	0.0001	0.0001	0.0000	0.0001	0.0001	0.0004	0.0004	0.0002
Compartment										
15	54.8	54.8	49.5	48.1	50.2	3.43	3.74	3.48	3.41	3.94
30	53.5	53.6	52.6	51.4	50.6	3.46	3.36	3.31	3.71	3.95
54	38.8	38.3	39.0	40.1	44.3	4.26	3.89	5.02	5.39	5.56
55	63.9	61.1	63.5	61.1	62.7	4.15	4.14	4.76	4.86	4.73
P-value	0.5090	0.5721	0.5606	0.5657	0.6063	0.6906	0.8939	0.6256	0.5503	0.6116

CON = control; CAT = catastrophic simulation; DOW = down removal; ALL = all removal.

[a] LSD test run at significant difference of α = 0.0500. Means with the same letter were not significantly different from other treatments or compartments for that given year.

The 1997 cohort significantly decreased in density and volume for both logs ($P = 0.0020$ and $P = 0.0003$, respectively) and snags ($P = 0.0019$ and $P = 0.0000$, respectively) since 1997 (table 2). The 1997 cohort log density has been reduced by 15 percent, while log volume has been reduced by 21 percent. The 1997 cohort snag density and volume have been reduced by 68 and 70 percent, respectively. Pine snags > 25 cm d.b.h. have fallen at a greater rate since 1997, with 52 percent of the density and 59 percent of the volume down. Ninety percent of the volume lost came from snags > 25 cm d.b.h., while only 43 percent of the density lost came from large snags. The 1998, 1999, and 2000 cohorts have decreased in log density and volume, but at most by a tenth. They have significantly decreased in snag density since their origin year by as much as half for the 1998 cohort ($P = 0.0174$, $P = 0.0027$, and $P = 0.0271$, respectively). Only 1998 and 1999 cohorts have significantly decreased in snag volume, with two-thirds of the 1998 cohort volume fallen ($P =$ 0.0.0493 and $P = 0.0038$, respectively). Thus, in these loblolly pine forests subjected to periodic fire, 50 percent of the snags generated in a given year might only be expected to stand for 3 to 4 years, especially large pine snags.

ACKNOWLEDGMENTS

The study was begun under the direction of James McMinn and was passed on to the present author upon Dr. McMinn's retirement in 2000. Research was funded by the U.S. Department of Energy, Savannah River Biodiversity Program, through the U.S. Department of Agriculture Forest Service. I thank J. Blake for his logistical and research support. Thanks are extended to the following who contributed to the study: E. Andrews, J. Blake, M. Howard, A. Malcolm, B. Miley, J. Miley, and E. Olson.

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MISSISSIPPI'S NEW FORESTRY BEST MANAGEMENT PRACTICES VIDEO

Andrew James Londo and John Benkert Auel[1]

POSTER SUMMARY

Mississippi's latest version of forestry best management practices (BMPs) for water quality was released in 2000. In conjunction with this release, funds were obtained through a Section 319H grant from the Mississippi Department of Environmental Quality to create a new BMPs video. Additional assistance was obtained from Georgia Pacific, PlumCreek, Weyerhaeuser, the Mississippi Forestry Commission, and Provine Helicopters. Video production started in the spring of 2001.

The first step was to create a video script. This was critical to make sure that we got the video footage we needed to help minimize costs, while assuring that all necessary material was covered. Great care was taken in the development of the script to provide as much information as possible about water-quality objectives and the need for BMPs on all the lands of Mississippi. Once the script was written and approved, video footage was collected.

This video encompasses all the steps necessary for completing water-quality objectives on forest land. Attention was given to planning a harvest, harvesting timber, site preparation concerns, and planting and communication between the landowner, logger, and forester.

Video footage was collected from old file footage, scenes of the previous BMP video produced in 1991, as well as new footage. On several occasions, arrangements made to film a given area had to be cancelled due to adverse weather. One site, which consisted of two video segments, took over 3 months to film.

Several different sites were used in making the film. This provided a broad representation of terrain features within the State, offering viewers a better chance of observing BMPs on the type of land with which they are most familiar. The types of BMPs used on each different land type really do not change; however, it was important to ensure that the film was representative of the entire State. Sites included flat areas from central Mississippi, rolling hills of the southeast, and the steeper terrain of the north.

During and following filming, the video producer edited and put together the video footage, combined with the narration of the video script, to produce the video itself. Final editing was completed with the assistance of the Department of Forestry to help assure that only complete and pertinent information was included. This tape has been used extensively for landowner training, logger training, and some forester training. There have been numerous requests for copies from Mississippi as well as several other States. To date, over 300 copies of the video have been distributed nationwide.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

VOLUME, MASS, AND NUTRIENTS OF DOWN WOODY DEBRIS FOLLOWING INITIAL SHORTLEAF PINE-BLUESTEM GRASS RESTORATION ACTIVITIES IN THE OUACHITA MOUNTAINS OF ARKANSAS

Jessica C. Seifert, Hal O. Liechty, Martin A. Spetich, and Daniel A. Marion[1]

Abstract—The Ouachita National Forest is restoring pine-mixed hardwood forests to a shortleaf pine-bluestem grass ecosystem through harvesting, midstory control, and the application of prescribed fire. Mean mass and volume of downed woody debris (DWD) in plots following initial harvesting and midstory-control were respectively 335 percent and 253 percent greater than in plots that had no restoration activities. Harvesting and midstory control also increased the mean DWD contents of C and N by 308 percent and 369 percent, respectively. The initial restoration fire reduced DWD mass in the shortleaf pine-bluestem plots by 27 percent and DWD volume by 28 percent. C and N contents in DWD were also significantly reduced by the initial restoration fire (26 percent and 32 percent) but were still 205 percent and 169 percent greater than in plots without restoration activities.

INTRODUCTION

Downed woody debris (DWD) frequently contains a significant portion of a forest ecosystem's accumulated carbon and nutrients (Hutson 1996, Maser and Trappe 1984, Muller and Liu 1991). Woody debris is especially important as a source of nutrient inputs to soils when other reserves of nutrients, such as forest floor and herbaceous biomass, have been removed by fire (Harmon and others 1986).

Historically, the Ouachita Mountains of Arkansas and Oklahoma were dominated by pine, pine-hardwood, and mixed oak communities with an herbaceous understory (Bukenhofer and Hedrick 1997). The shortleaf pine (*Pinus echinata* Mill.)-bluestem grass (*Andropogon* spp.) ecosystem was an important component of this landscape and consisted primarily of a low-density pine overstory (13.8 to 16.1 m^2 ha^{-1} basal area) with a floristically rich grass and forb understory maintained by fire (Bukenhofer and Hedrick 1997, Masters and others 1995, Spetich and others 2002). Due to fire suppression and commercial harvesting, the Ouachita Mountain landscape today is drastically different. A dense midstory of pine and hardwood trees has encroached, woody vegetation now dominates the understory, and the once prolific grasses are uncommon (Bukenhofer and Hedrick 1997, Bukenhofer and others 1994, Spetich and others 2002).

The Ouachita National Forest (ONF), located in west-central Arkansas and southeastern Oklahoma, plans to restore 62,730 of its 688,000 ha of pine and mixed hardwood forests to a shortleaf pine-bluestem grass ecosystem (Bukenhofer and Hedrick 1997, Bukenhofer and others 1994, Spetich and others 2002). This will be accomplished through overstory thinning, removal of the midstory, and application of moderate intensity fires at a 2- to 5-year interval to maintain the open condition of a shortleaf pine-bluestem community (Spetich and others 2002).

To better understand the impacts of restoration activities on carbon storage and nutrient availability, an intensive study was initiated in two watersheds, one of which is being restored to a shortleaf pine-bluestem community and the other, which is being maintained in its current condition. As part of this larger study, we are evaluating the impacts of the restoration activities on DWD carbon and nutrient pools. In this paper, we evaluate the changes in DWD mass and volume as well as DWD carbon and nitrogen content that occurred following the initial overstory thinning, midstory competition control, and prescribed fire.

METHODS

This study utilized two adjacent sub-watersheds of the Upper Lake Winona Watershed located in the northeastern portion of the Ouachita Mountains in Arkansas (fig. 1). The two sub-watersheds have similar geology, soils, and landform structure. The 908-ha South Alum Creek sub-watershed (control) is a combination of shortleaf pine, pure hardwood, and mixed pine-hardwood stands with a high

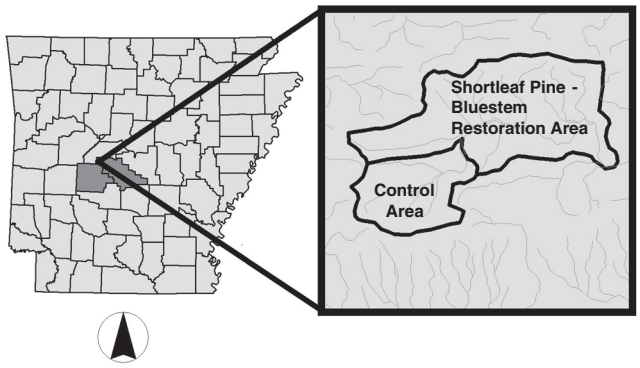

Figure 1—Location of North Alum Creek Sub-Watershed (shortleaf pine-bluestem restoration area) and South Alum Creek Sub-Watershed (control area) in Saline and Garland Counties in west-central Arkansas.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

basal area (25.3 to 27.6 m^2 ha^{-1}) and a dense midstory. The 1,364-ha North Alum Creek sub-watershed is being managed to create a shortleaf pine- bluestem ecosystem (pine-bluestem restoration area). This is accomplished through the felling of overstory hardwoods and pines (reducing the total basal area by approximately 50 percent), followed by the felling of midstory trees and brush, and the application of prescribed fires on a 2- to 5-year interval. Due to poor local hardwood markets, only pine timber was merchandised. Hardwood timber and midstory vegetation were left where they fell. The harvesting and midstory control activities took place in late fall of 2000 through spring of 2001. The initial prescribed fire occurred in February 2002. No restoration or management activities occurred in the control area during this time period.

Six 0.08-ha plots that received the entire suite of restoration activities in the shortleaf pine-bluestem area and five 0.08-ha plots in the control area were studied. To quantify the amount and nutrient content of fine DWD (< 7.6 cm in diameter) and coarse DWD (≥ 7.6 cm in diameter) in these plots, the volume of DWD was inventoried and samples were collected for specific gravity, C concentration, and N concentration determination. Inventory and sampling occurred in the fall of 2001 after harvesting and midstory competition control and again in the spring and summer of 2002 following the initial prescribed fire. DWD less than 10.1 cm in diameter was inventoried on each plot using the planar intersect method described in Brown (1974). Pieces of debris less than 10.1 cm in diameter that intersected one of four 16.1-m transects, arranged 90° to one another, were tallied and used to calculate volume. Because four transects were established on each plot, the length of the transect used to inventory fine DWD was staggered to prevent all fine debris from being inventoried from the center of the plot. The 16.1-m transects were extended 15.2 m off plot for specific gravity and nutrient sample collection. Volume was calculated using an equation modified from Van Wagner (1964). For DWD greater than 10.1 cm in diameter, the mid-length diameter and length of every piece on a plot was measured using methods described in Spetich and others (2002). The cylindrical volume of each piece was then calculated. The mass of all DWD was determined using specific gravity measurements and the volume inventories. C and N were quantified by combustion using a LECO C/N analyzer. The mass was used in conjunction with the nutrient analyses to determine the C and N content of the DWD. The temperature of the restoration fire was determined on the shortleaf pine-bluestem plots using tiles painted with temperature-indicating liquids, which liquefy and evaporate at specific indication temperatures. The median temperature of the prescribed fire was 202 °C at the soil surface and 138 °C approximately 30 cm above the soil surface.

Welch's t-tests ($\alpha = 0.05$) were used to quantify the effects of the harvesting and thinning operations on the treatment area and to document initial differences between the shortleaf pine-bluestem restoration area and the control. Paired t-tests ($\alpha = 0.05$) were used to determine significant differences due to the initial restoration fire. The assumption of normality for each t-test was confirmed using the Shapiro-Wilk test.

RESULTS AND DISCUSSION

Harvesting and Midstory Control

Total DWD volumes after the initial overstory harvest and midstory removal were 253 percent greater in the shortleaf pine-bluestem plots (122.9 m^3 ha^{-1}) than in the control plots (34.8 m^3 ha^{-1}) (table 1). In the control plots, mean volumes of fine (17.2 m^3 ha^{-1}) and coarse DWD (17.6 m^3 ha^{-1}) were similar. However, there was 32 percent more coarse DWD than fine DWD volume in the shortleaf pine-bluestem plots. Within the control plots, pine comprised the majority of the DWD (64 percent), but in the shortleaf pine-bluestem plots, pine accounted for only 41 percent of the total DWD. The higher levels of DWD in the shortleaf pine-bluestem plots are likely a result of overstory harvesting and midstory control activities. The relatively greater volumes of hardwood DWD compared to pine DWD were related to the lack of local commercial markets for hardwoods resulting in midstory trees and hardwoods being left on the site. Harvesting and removal of merchantable pine boles resulted in a lack of any significant increase in coarse pine DWD within the shortleaf pine-bluestem plots. This resulted in an increase in the ratio of hardwood to pine DWD in the shortleaf pine-bluestem plots.

Mean DWD mass was significantly greater in the shortleaf pine-bluestem plots than in the control plots. Generally these differences in mass were similar to differences observed in DWD volumes. However, differences in DWD mass between the shortleaf-pine bluestem and control plots were greater than those observed for volume due to differences in specific gravity between pine and hardwood DWD, along with high specific gravity of the fresh undecomposed hardwood DWD that was left following harvesting and midstory control. Total mass of DWD was 335 percent greater whereas total volume of DWD was only 253 percent greater in the shortleaf pine-bluestem plots compared to control plots. Hardwood DWD mass was 678 percent greater in the shortleaf pine-bluestem plots (43.1 Mg ha^{-1}) than in the control plots (5.5 Mg ha^{-1}) (table 1). Hardwood DWD mass accounted for 64 percent of the total DWD mass in the shortleaf pine-bluestem plots but only 36 percent in the control plots. Harvesting and midstory control activities in the shortleaf pine-bluestem plots appeared to have dramatically increased the ratio of hardwood to pine DWD mass in the restoration area as well as the total mass of DWD.

As a result of the higher levels of DWD, mean C and N contents were also greater in the shortleaf pine-bluestem plots (30.9 Mg ha^{-1} and 139.4 kg ha^{-1}) than in the control plots (7.6 Mg ha^{-1} and 29.7 kg ha^{-1}) (table 1). Fine DWD contained 41 percent of the total DWD C in the control and shortleaf pine-bluestem plots. This was similar to the overall contribution of fine DWD to the total DWD mass. However, 53 percent of the N in DWD was contained in fine DWD. This was due to the higher N concentration in the fine DWD (0.26 percent) than in the coarse DWD (0.16 percent). Concentrations of C in fine (46 percent) and coarse DWD (47 percent) were similar. Overall N concentrations of fine hardwood DWD (0.49 percent) were much higher than fine pine DWD (0.19 percent), coarse hardwood DWD (0.21 percent), or coarse pine DWD (0.10 percent). The particular restoration harvesting and midstory control activities utilized in the shortleaf pine-bluestem plots increased the

Table 1—Mean volume, mass, C content, and N content of pine and hardwood downed woody debris before the initial shortleaf pine-bluestem restoration fire on the control and shortleaf pine-bluestem restoration area

Treatment	Fine DWD			Coarse DWD			Total DWD		
	Pine	HWD	Total	Pine	HWD	Total	Pine	HWD	Total
	volume (m^3 ha^{-1})								
Control	8.2a[a]	9.0a	17.2a	14.1a	3.5a	17.6a	22.3a	12.5a	34.8a
SP-B	22.7b	30.3b	53.0b	28.0a	41.9b	69.9b	50.7a	72.3b	122.9b
	mass (Mg ha^{-1})								
Control	3.3a	4.1a	7.4a	6.7a	1.5a	8.2a	10.0a	5.5a	15.5a
SP-B	9.9b	17.1b	26.9b	14.3a	26.0b	40.4b	24.2a	43.1b	67.3b
	carbon content (Mg ha^{-1})								
Control	1.5a	1.8a	3.4a	3.6a	0.6a	4.2a	5.1a	2.5a	7.6a
SP-B	4.6b	7.6b	12.2b	7.1a	11.6b	18.7b	11.7a	19.2b	30.9b
	nitrogen content (kg ha^{-1})								
Control	8.3a	12.3a	20.6a	6.5a	2.7a	9.2a	14.7a	15.0a	29.7a
SP-B	17.3b	51.6b	68.9b	14.1a	56.4b	70.5b	31.4b	108.0b	139.4b

SP-B = shortleaf pine-bluestem; DWD = downed woody debris; HWD = hardwood.
[a] Means for control and SP-B areas with the same letter for a given DWD component and parameter do not significantly differ at α = 0.05.

contents of C and N by increasing the mass of DWD. These practices also altered the species composition and ratio of fine to coarse DWD following initial restoration activities. These alterations appear to change the C:N ratio in the DWD of the shortleaf pine-bluestem areas as well.

Initial Restoration Fire

The initial restoration fire reduced mean DWD volumes in the shortleaf pine-bluestem plots by 28 percent (from 122.9 to 88.5 m^3 ha^{-1}) (table 2). Fine DWD accounted for the majority (60 percent) of this reduction in DWD volume because fine fuels ignite and are consumed more readily than coarse DWD. There was not a statistically significant loss of coarse DWD volume when both pine and hardwoods were included in the analysis. However, the mean volume of coarse hardwood DWD was significantly reduced from 41.9 to 35.6 m^3 ha^{-1} whereas fine hardwood DWD volume was reduced from 30.3 to 17.5 m^3 ha^{-1} (42 percent). Reductions in the fine pine DWD were not significant. We suspect that the high variability in pine DWD among plots was responsible for the lack of statistically significant reductions in pine DWD. DWD volumes measured in the control plots before and after the initial restoration fire in the shortleaf pine-bluestem area generally differed by less than 0.5 m^3 ha^{-1}, indicating little or no change in DWD volumes in these watersheds as a result of severe climatic conditions or mortality.

The losses in DWD mass due to the prescribed fire in the shortleaf-pine bluestem plots were similar to the volume losses. The overall mass of DWD was reduced 27 percent, from a mean of 67.3 to 48.9 Mg ha^{-1}, whereas the volume was reduced 28 percent (table 2). Fine DWD accounted for 57 percent of the overall loss. Although the reduction of mass was statistically significant, the DWD mass in the shortleaf pine-bluestem plots (48.9 Mg ha^{-1}) following the fire was still 218 percent greater than in the control plots (15.4 Mg ha^{-1}). The prescribed fire did not alter the ratio of hardwood to pine DWD. Hardwoods made up 64 percent and 65 percent, respectively, of the total DWD mass before and after the initial restoration fire. The restoration fire amplified the difference between the coarse to fine DWD ratios in the shortleaf-pine bluestem plots. Coarse DWD made up 60 percent of the total DWD mass in the shortleaf pine-bluestem plots prior to the initial prescribed fire but made up 67 percent after the fire. Only 44 percent of DWD in the control plots was in the coarse size class.

Carbon losses in the shortleaf pine-bluestem were, as expected, similar to losses of DWD mass. Mean C content was reduced from 30.9 to 22.9 Mg ha^{-1}, a loss of 26 percent. Mean N DWD content in the shortleaf pine-bluestem plots was reduced by 32 percent, from 139.4 to 95.2 kg ha^{-1} (table 2). Even with these losses, C and N contents following the prescribed fire were respectively 205 and 169 percent greater in the shortleaf pine-bluestem plots than in the control plots. The reduction of N in DWD does not mean that this nutrient was lost from the ecosystem. Our sampling methods did not measure any ash additions to the forest floor/mineral soils or whether N was volatilized, oxidized, or redistributed off site through convection.

The fire had little impact on C or N concentrations. Mean C concentrations were unchanged (47 percent) in coarse DWD and only increased from 46 percent to 47 percent in fine DWD. Mean N concentrations before and after the fire were also similar in both the coarse DWD (0.26 percent to 0.27 percent) and fine DWD (0.16 percent to 0.15 percent). The fire did slightly alter the C:N ratio in the shortleaf pine-bluestem from 222:1 prior to the fire to 240:1 after the fire.

Table 2—Mean volume, mass, C content, and N content of pine and hardwood downed woody debris in the shortleaf pine-bluestem restoration area before and after the initial restoration fire

	Fine DWD			Coarse DWD			Total DWD		
Treatment	Pine	HWD	Total	Pine	HWD	Total	Pine	HWD	Total
	volume (m^3 ha^{-1})								
Before	22.7a[a]	30.3a	53.0a	28.0a	41.9a	69.9a	50.7a	72.3a	122.9a
After	15.1a	17.5b	32.6b	20.3a	35.6b	55.9a	35.5a	53.0b	88.5b
	mass (Mg ha^{-1})								
Before	9.9a	17.1a	26.9a	14.3a	26.0a	40.4a	24.2a	43.1a	67.3a
After	6.6a	9.8b	16.4b	10.8a	21.8b	32.5b	17.3b	31.6b	48.9b
	carbon content (Mg ha^{-1})								
Before	4.6a	7.6a	12.2a	7.1a	11.6a	18.7a	11.7	19.2a	30.9a
After	3.1a	4.6b	7.7b	5.3a	9.9b	15.2b	8.4	14.4b	22.9b
	nitrogen content (kg ha^{-1})								
Before	17.3a	51.6a	68.9a	14.1a	56.4a	70.5a	31.4a	108.0a	139.4a
After	11.2a	33.3b	44.4b	13.1a	37.7b	50.8b	24.2a	71.0b	95.2a

DWD = downed woody debris; HWD = hardwood.

[a] Means before and after the fire with the same letter for a given DWD component and parameter do not significantly differ at $\alpha = 0.05$.

This was most likely due to decreases in fine DWD, which had lower C:N ratios than did coarse DWD.

CONCLUSIONS

The initial restoration activities of overstory harvesting and midstory control added significant amounts of DWD and associated N and C content to the restoration area. Had hardwood timber been marketed, the additions of coarse DWD and hardwood DWD would probably have been less. The initial restoration fire removed a significant amount of DWD as well as C and N contained in the DWD. However, even after the initial restoration fire, there was still significantly more DWD and associated N and C on the shortleaf pine-bluestem plots than on the control. Due to the spatial heterogeneity in harvesting and fire that occurs in an area being restored to a shortleaf pine-bluestem ecosystem and because of our selection of only shortleaf pine-bluestem plots that received the full complement of restoration activities, changes of DWD in this study most likely overestimate the true changes that occurred over the 1,364-ha watershed.

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FORECASTING SHORTLEAF PINE SEED CROPS IN THE OUACHITA MOUNTAINS

Michael G. Shelton and Robert F. Wittwer[1]

Abstract—We field tested a cone-rating system to forecast seed crops from 1993 to 1996 in 28 shortleaf pine (*Pinus echinata* Mill.) stands, which represented a wide range of stand conditions. Sample trees were visually assigned to one of three cone-density classes based on cone spacing, occurrence of cones in clusters, and distribution of cones within the crown. Classification took < 1 minute per tree, permitting a large number of trees to be evaluated rather than making precise counts on a few trees. The stand's mean cone rating and basal area explained 82 percent of the variation in sound seed production; however, the developed prediction equation had a large root mean square error (257,000 seeds per acre). Our cone-rating system did well in forecasting the poor and good seed crops. However, more precise determinations of both cone and seed density are probably warranted when seed crops are forecast to be marginal for stand regeneration.

INTRODUCTION

The largest concentration of shortleaf pine (*Pinus echinata* Mill.) is in the Ouachita Mountains of Arkansas and Oklahoma, where it can be successfully regenerated by both natural and artificial means (Lawson 1990). The greatest challenge to successful natural regeneration is providing an adequate seed supply on a receptive seedbed with low levels of competing vegetation (Cain 1991, Shelton and Cain 2000). This is especially true in the Ouachita Mountains, where shortleaf pine seed crops are erratic and successive years of low seed production often occur (Shelton and Wittwer 1996; Wittwer and Shelton, in press; Wittwer and others, in press). Seed production within a stand can be enhanced by selecting the appropriate reproduction cutting method, retaining productive trees as indicated by the presence of older cones, and promoting tree vigor. However, the greatest variation in seed crops is due to uncontrollable annual fluctuations that reflect differences in weather, insects and pathogens, and internal cycles within the trees. Because of this, shortleaf pine seed crops can vary from nil to over a million seeds per acre. Being able to forecast the size of upcoming seed crops in advance of seed dispersal would greatly aid land managers in scheduling silvicultural operations, such as stand harvesting and site preparation.

In this paper, we report a procedure for forecasting shortleaf pine seed crops in the Ouachita Mountains. The procedure visually assigned trees to three cone-density classes, which permits observers to rate a large number of trees rather than making detailed counts on a few trees. The procedure was tested in 28 shortleaf pine stands that were both evaluated for cone density and monitored for seed production from 1993 to 1996. Preliminary results of the forecasting system have been published earlier (Shelton and Wittwer 1995).

METHODS

Study Area

The study area extended from eastern Oklahoma through central Arkansas, and included 28 stands that were being monitored for seed production in conjunction with various studies of natural shortleaf pine regeneration (table 1). Eighteen stands were part of the Ecosystem Management Research in the Ouachita Mountains (Baker 1994) and included the following treatments: pine and pine-hardwood seed tree, pine and pine-hardwood shelterwood, and pine single-tree selection. There were three or four stands for each treatment. These 40-acre stands were located throughout the Ouachita Mountains, except for the extreme eastern part. There, the pine-only treatments of two research studies (shelterwood and single-tree selection) were used for our seed-forecasting study in addition to an operational-level seed-tree stand. Each research area was considered a single stand or replicate. Sampling was conducted in a total of 2 to 3 acres within each research area and the operational stand, but the sampled area was surrounded by a larger area with the same pine basal area. In the western part of the Ouachita Mountains, seven 22- to 40-acre operational-level stands were evaluated for cone density

Table 1—Characteristics of the 28 shortleaf pine stands in the Ouachita Mountains evaluated for cone rating and seed production

Stand type	Number	Basal area[a]	
		Mean	Range
		square feet per acre	
Seed tree	10	13.4	8.0-17.5
Shelterwood	8	36.1	26.7-48.0
Single-tree selection	9	52.1	40.4-65.0
Unmanaged sawtimber	1	98.3	—

[a] Trees ≥ 10 inches d.b.h.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

and seed production. There was one seed-tree stand, one shelterwood stand, four single-tree selection stands, and one unmanaged sawtimber stand.

In the research stands, basal area was determined on four to six plots per stand ranging from 0.1 to 0.7 acre in area. In the operational-level stands, basal area was determined with a 10 basal-area-factor prism at a point centered over each seed trap used for monitoring seed production.

Cone-Rating Procedures

We modified a cone-rating procedure that was developed for western conifers (McDonald 1992, Rietveld 1978, Schubert and Pitcher 1973) by employing several quantitative and qualitative features that permit rapid evaluation of the cone density in a tree's crown. Cone density was visually rated based on cone spacing, the occurrence of cones in clusters, and the distribution of cones within the crown (table 2). Development of guidelines for evaluating each element was described more fully in Shelton and Wittwer (1995). In our procedure, cone density was rated only for the side of the crown facing the evaluator (that is, the crown face). In application, the cone rating of trees was an integration of all features to choose the proper cone-density class. Similar visual-rating systems have also been developed for evaluating crown density as an expression of tree vigor (Belanger and Anderson 1989).

For good visibility, evaluators stood one to two tree heights away from the sample tree with the sun to their back and used high-quality 7-power binoculars. Most trees were classified when maturing cones were most visible—in the early morning or late afternoon and on days with low cloud cover and light winds. Stands were evaluated from late July through early September. A total of six evaluators rated stands; in some cases two evaluators rated different areas within the same stand. Maturing cones were distinguished from older cones of previous years based on the following criteria: (1) maturing cones were yellowish green to green compared with dark brown for older cones, (2) maturing cones were closed while older cones were open when dry, and (3) maturing cones were among the needles while older cones were farther back from the tip where needles had been cast. Evaluation was avoided on cloudy days following a rain because the older cones were closed and the low light intensity made the color differences subtle.

Table 2—Cone-density classes used to rate shortleaf pine sample trees

	Cone-density class		
Property	Few	Average	Good
Spacing between cones (*feet*)	> 7	2.5 – 7	< 2.5
Multiple cones on branchlets	Rare	Occasional	Common
Distribution within crown	Erratic	Upper half	Uniform
Cones per crown face	< 10	10 – 80	> 80

Source: Shelton and Wittwer (1995).

Cone density was rated for two or three sample trees of seed-producing sizes—that is, ≥ 10 inches diameter at breast height (d.b.h.)—randomly selected within one to two tree heights from each seed trap used for monitoring seed production.

Numerical values were arbitrarily assigned to the three cone-density classes as follows: 0 for few, 1 for average, and 2 for good. However, the rating of sample trees was modified to accommodate borderline occurrences of classes by assigning pluses and minuses in the field tally. A plus indicated the tree was near the upper limits of the class, while a minus indicated the lower limits. Such variation would probably have averaged out, but it may have been critical in situations where a high percentage of the trees were near a class limit. Most important, assignment of pluses and minuses prevented evaluators from dwelling on the class of borderline sample trees. For calculating stand averages, a value of 0.3 was added to the class value for a plus or subtracted for a minus (for example, a "1+" had a value of 1.3, and a "1–" had a value of 0.7).

Seed Production

The number and type of seed traps used for monitoring seed production varied from study to study. Eighteen 0.86-square-foot seed traps were used in each of the Ecosystem Management Research stands (Wittwer and others, in press). For the research areas and seed-tree stand in the eastern Ouachita Mountains, seeds were collected in nine to sixteen 0.86-square-foot seed traps in each area or stand (Wittwer and Shelton, in press). Six to ten 4-square-foot seed traps were used in each of the operational-level stands in Oklahoma (Wittwer and Shelton, in press).

As a minimum, seeds were collected at the middle and end of the October-to-February monitoring period of each year. Seed viability was usually determined by splitting seeds and inspecting the contents (Bonner 1974). Seeds with full, firm, undamaged, and healthy tissue were judged to be potentially viable and were tallied as sound seeds. For large collections in the 4-square-foot seed traps, seeds were considered sound if they sank in ethanol (Krugman and Jenkinson 1974). A subsample of these seeds was split, and the flotation test yielded the same results as the split test.

Data Analysis

A common observation of studies making precise cone counts is that they tend to underestimate the actual number of cones on the tree because all the cones on the crown face are not visible from a single observation point. Such bias undoubtedly also occurred in our procedure, but it was corrected by using cone rating as a predicator of observed seed production in shortleaf pine stands that were evaluated for both cone rating and seed production from 1993 to 1996.

Cone rating and seed production were averaged for each stand and year, and basal area was averaged for each stand using the closest available inventory to midpoint of the monitoring period. The 18 stands from the Ecosystem Management Research were not sampled in 1993.

Regression was then used to evaluate the effects of basal area and cone rating as predictors of the stand's seed production as follows:

$$S = b_o + B^{b1}R^{b2}, \quad (1)$$

where

S = thousands of sound pine seeds per acre
B = basal area in square feet per acre in shortleaf pine trees ≥ 10 inches d.b.h.
R = mean cone rating
b = coefficients to be determined by nonlinear regression (SAS Institute 1988).

This approach allowed the regression coefficients to compensate for the effects of (1) the number of seeds per cone, (2) underestimation of the actual number of cones on trees by evaluators, (3) the arbitrary numerical values assigned to cone-rating classes, and (4) conversion of cone density for the crown face to values for the tree. An intercept coefficient was needed in the equation, because there may have been up to nine cones visible to the evaluator even though a tree received a zero cone rating. Examination of the residuals indicated an unequal error variance, which was reduced by square root transformation of the seed-production data. The final equation was retransformed for presentation and for calculation of fit statistics as described by Schlaegel (1982).

RESULTS AND DISCUSSION

The seed crops from 1993 through 1996 were highly variable, ranging from complete failures to bumper crops; yearly averages were 857, 70, 3, and 465 thousand sound seeds per acre, respectively. Geographically, the lowest production occurred in eastern Oklahoma.

Sound seeds (1,000 per acre) can be predicted from stand basal area (square feet per acre) in trees ≥ 10 inches d.b.h. and cone rating by the following equation:

$$S = \left(1.328 + B^{0.8004}R^{1.833}\right)^2 \quad (2)$$

Number of observations was 92, root mean square error was 257,000 seeds per acre, and fit index was 0.82.

Figure 1 compares predicted with observed seed production for equation 2. The wide variation in seed production that occurred over the 4-year period was apparent; observed values ranged from zero to over 3 million seeds per acre. The greatest deviations between predicted and observed values were for the larger seed crops; this pattern is common in biological relationships. Cain and Shelton (2001) state that from 40,000 to 90,000 sound seeds per acre are required to successfully regenerate mixed stands of loblolly (*P. taeda* L.) and shortleaf pines in the west Gulf Coastal Plain. Thus, we feel that a reasonable lower threshold for shortleaf pine in the Ouachita Mountains would be 50,000 sound seeds per acre, because shortleaf generally has a lower seedling-to-seed ratio than loblolly pine (Shelton and Cain 2000). Examination of the residuals indicated that a decision

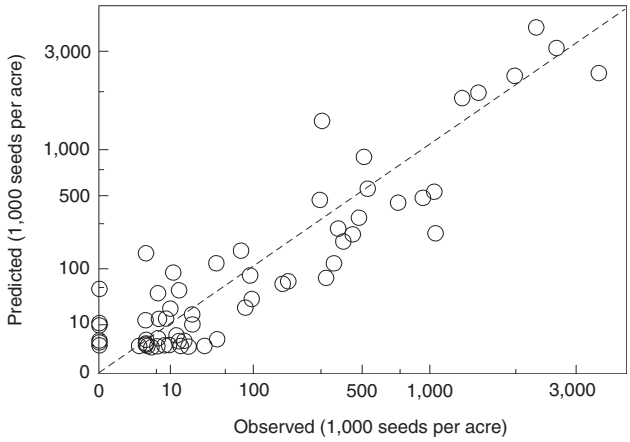

Figure 1—Predicted production of sound seeds plotted against observed values for shortleaf pine stands in the Ouachita Mountains. The dashed line represents equal values. Twenty-nine symbols are hidden along the lower part of the Y axis. The axes are in cubed-root scale.

based on predicted values and this threshold would have been correct for observed seed production in 94 percent of the stands and years. In 4 percent of the stands and years, seed production was predicted to be adequate but was not, while seed production was predicted to be inadequate in 2 percent of the stands and years but was actually adequate. There did not seem to be any pattern with evaluator, stand type, or geographic location in these decision errors.

Several obvious sources of error are associated with our forecasting procedure. Sampling error is associated with each variable in equation 2. For example, differences undoubtedly existed among the people rating cone density. After a 1-hour training session, the six evaluators in this study rated the same six trees in seven different shortleaf pine stands. The mean stand rating for evaluators had a coefficient of variation that averaged 14 percent in six of the stands. In the seventh stand, the coefficient of variation was 66 percent. This stand had a mean rating of only 0.11, so apparently a few trees near a class break can increase variation among the evaluators, especially when the rating is low.

Another source of variation is the number of sound seeds per cone. Our forecasting procedure does not include a sampling scheme to determine this value. Thus, the seed density in cones was intrinsically accounted for in the cone rating. Wakeley (1954) reported that shortleaf produces 25 to 35 sound seeds per cone during good years, and values are reduced by about one-half during poor years. Procedures for estimating the seed yields from cones exist (for example, Bramlett and Hutchinson 1964, McLemore 1962), but additional sampling is required. Such evaluations are most likely needed when seed production is predicted to be marginal.

Values generated from equation 2 are plotted in figure 2, which shows that a given level of seed production can be achieved by an array of basal areas and cone ratings. High basal areas coupled with low cone ratings can yield the same seed production as low basal areas and high cone

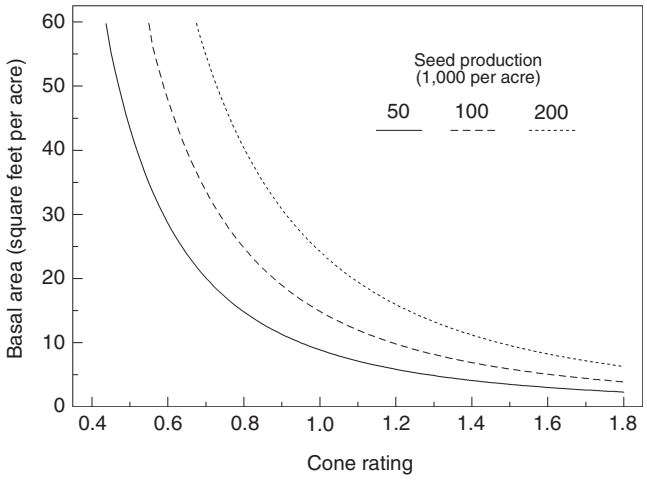

Figure 2—Combinations of cone rating and basal area that yield the specified sound seed production for shortleaf pine stands in the Ouachita Mountains. Data were calculated from equation 2.

ratings. Figure 2 can also be used to judge the acceptability of the upcoming seed crop based on a stand's cone rating and basal area. If trees are to be harvested before seed dispersal, the stand's residual basal area should be used, and the cone rating should reflect the retained trees.

Our forecasting procedure requires visual rating of the cone density on sample trees, determining stand basal area, and estimating seed production with equation 2 or figure 2. The number of seeds required for successful regeneration depends on a myriad of factors that include seed predators, seedbed conditions, competing vegetation, weather, and overstory vegetation. These factors must also be viewed within the context of landowner goals. Thus, proposing guidelines for making silvicultural decisions about the adequacy of a seed crop should include sufficient latitude for the skill and judgment of trained foresters. If 50,000 to 100,000 sound seeds per acre are assumed to provide acceptable shortleaf pine natural regeneration, figure 2 suggests that guidelines for the minimum value for mean cone ratings should be 1.0 to 1.2 for seed-tree stands, 0.6 to 0.8 for shelterwood stands, and 0.4 to 0.7 for uneven-aged stands. Some confirmation of the presence of a reasonable number of sound seeds in cones is recommended, especially when the cone rating is at the lower end of these ranges.

CONCLUSIONS

The visual cone-rating procedure evaluated in this study provides some insight into the adequacy of the upcoming seed crop. This procedure is rapid and appears to be sufficiently accurate to aid in making silvicultural decisions about the intensity and timing of site preparation and possibly the scheduling of reproduction cutting. Cone density can be rated in early July when developing cones are near their fully mature size. Consequently, this forecasting procedure provides a maximum lead time of about 4 months before the peak in seed dispersal. Longer lead times are possible with silvicultural treatments that do not require application before seed dispersal for optimum effectiveness. For example, hardwood control can extend from the time of cone rating through the early part of the growing season following seed dispersal. If a bumper seed crop was forecast, prescribed burning for site preparation might be extended later into the dormant season than is normal for optimizing seedling establishment (Cain 1986). The same logic could probably be extended to harvesting. In the Ouachita Mountains, where shortleaf pine seed crops are erratic, the greatest utility of this forecasting procedure would probably be in timing site preparation with the occurrence of an adequate seed crop and in matching the intensity of site preparation with the size of the anticipated seed crop.

An important goal of this study was to develop a keen appreciation for the entire pine reproductive cycle. For example, abundant numbers of both male and female flowers often indicate the potential for a good upcoming seed crop 18 months in advance of seed dispersal. Female flowers can be seen at the tip of the first flush in the spring using binoculars, and male flowers are easily visible when they fall to the ground in the late spring. This awareness can give longer lead times, especially when coupled with our forecasting procedure to provide confirmation during the summer before dispersal.

ACKNOWLEDGMENTS

The authors thank Leif Anderson, Rodney Howell, Mike Huebschmann, and Saul Serna for their assistance in this research.

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Forest Health

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HISTORY OF PIEDMONT FORESTS: IMPLICATIONS FOR CURRENT PINE MANAGEMENT

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Abstract—Piedmont forests were maintained for millennia in an open condition by anthropogenic- and lightning-ignited fires. After European settlement, row-crop agriculture caused serious soil erosion, making Piedmont soils less capable of supplying moisture and nutrients during drought periods. Dense stands of pine, both naturally and artificially regenerated over the past 70 years, are severely stressed on these soils and become highly susceptible to infestations of the southern pine beetle (SBP). The current SPB epidemic and depressed smallwood markets serve as a disincentive to invest in expensive reforestation. Prescribed burning, or herbicide applications where burning is not feasible, along with thinnings and timely harvests, should be used to maintain relatively open stands and encourage herbaceous vegetation. A Piedmont forest landscape consisting of a shifting mosaic of low-density pine stands in all seral stages, intermixed with hardwood and pine-hardwood stands, should reduce the intensity of SPB attacks and provide many commodity and noncommodity values desired by landowners and society.

INTRODUCTION

Loblolly pine (*Pinus taeda* L.) has been planted in the Piedmont physiographic region for more than 70 years. The species has been used to reclaim much of the severely eroded soils that were abused during the corn and cotton farming era from 1700 – 1930s. Reclamation of the worn-out farmland to productive forest land throughout large areas of the Piedmont has proven to be a major conservation success story. However, there is concern for pine plantation management, as now practiced, in the Piedmont. Recent southern pine beetle (SPB) epidemics, combined with depressed pine stumpage prices, have devastated many pine plantations in the region causing millions of dollars in damage (www.srs.fs.fed.us/research/4501/). These huge losses have become a disincentive to landowners considering investing in pine plantation management. The recent drought has exacerbated SPB damage. Landowners and forest managers must anticipate periodic droughts and avoid dense pine plantations on eroded soils in the Piedmont.

Because of the extensive damage done by SPB in recent years, it is timely to examine the land-use history of the Piedmont and determine if the past could provide insight to develop new management scenarios for this region. In this paper, we examined the effects of man's historical activities on the Piedmont landscape, from the early Native Americans to the European/African agricultural influence to the modern period of rapid population growth, pine plantation management, and landscape fragmentation. We report how land-use history can be used to suggest alternatives to contemporary pine management to enhance forest health and sustainability.

HISTORICAL LAND-USE IN THE PIEDMONT

Native Americans

Native Americans have been in the southern Piedmont for at least 12,000 years (Carroll and others 2002). They used fire extensively to manipulate and manage the landscape. Because of frequent burning by Native Americans and lightning-ignited fires, the Piedmont landscape, as well as much of the South's forests, was probably open and park-like with prairies, savannahs, and woodlands commonly occurring throughout the landscape. At the time of Columbus, it is believed that as many as two million Native Americans occupied the South (Dobyns 1983), more than enough people to make a significant impact on the landscape through their burning and farming activities.

Natural lightning fire complemented the frequent burning regime of Native Americans. Unlike today's closed forests with dense underbrush, lightning strikes in open forests with grassy understories would have started many fires that would have burned vast acreages. Without Native American burning and lightning-ignited fires, it is unlikely that oak-hickory-pine forests would have dominated the Piedmont for thousands of years (Carroll and others 2002). Although oaks, hickories, and pines still dominate the Piedmont today, it is important to emphasize that the horizontal and vertical structure, as well as the understory composition, of historical forests were much different than forests of today. Those earlier forests were lightly stocked in the overstory, generally open in the midstory, and probably had a rich layer of herbaceous species (both grasses and forbs) that readily carried fire and benefited foraging by many wildlife species.

Post-European Discovery Until 1930

With the introduction of European diseases, the Native American population collapsed by 90 to 95 percent, and the southern forest encroached and gradually became the romanticized forest primeval of 18th century writers (Carroll and others 2002, Dobyns 1983). This was the forest that had to be cleared by early European settlers and their African slaves (Edgar 1998). The Piedmont was first cleared and settled in Virginia in the mid-1700s, and agriculture progressed steadily southward through North Carolina, South Carolina, and into Georgia (Trimble 1974).

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Erosion of the loamy topsoil from the relatively steep Piedmont slopes gradually increased as agriculture intensified. Corn, not cotton, was the major agricultural crop although cotton became the primary cash crop in the mid-1800s. After the Civil War, cotton production proliferated and, by 1929, had exceeded the land area in corn production (Healy 1985). Row-crop agriculture accelerated soil erosion over two centuries, washing away the fertility and moisture-supplying capacity of the Piedmont soils (Trimble 1974). By the late 1920s, crop agriculture was in rapid decline in the Piedmont. The loss of the soil's productive capability due to erosion, losses to the boll weevil, and development of synthetic fibers all contributed to the decline of cotton agriculture (Healy 1985). Although the productive capacity of the land had been markedly reduced by row-crop agriculture, economically viable forestry could still be practiced in most of the region. However, in the early decades of the 20th century, the primary goal was to reduce erosion and restore the productivity of the land (Healy 1985).

Forestry in the Piedmont

As agriculture became unproductive on the worn-out soils, people left the farms for the cities (Healy 1985). It was Franklin Roosevelt's administration dealing with the Great Depression of the 1930s that began public works projects to put people to work. The Civilian Conservation Corps (CCC) was created to reduce soil erosion and restore productivity to the land. Tree planting became a major conservation activity (fig. 1); early plantations were planted at 6- by 6-foot spacing by the CCC. Two other government programs have made a significant impact on landscape restoration and forest productivity. In the late 1950s and early 1960s, the Soil Bank Program produced a dramatic spike in numbers of seedlings planted (fig. 1). Later, the Conservation Reserve Program in the late 1980s caused another major increase in tree planting. Today, the average density of plantations is about 700 seedlings per acre (Schultz 1997).

Loblolly pine, shortleaf pine (*Pinus echinata*), and Virginia pine (*P. virginiana*) occur naturally throughout most of the Piedmont. After farms were abandoned, much of the Piedmont seeded in naturally on old agricultural fields and home sites from residual pine trees scattered throughout the region. Loblolly pine, in fact, was known as "old field pine" because of its propensity to occupy abandoned fields (Schultz 1997). Loblolly pine grows faster than other pines on all but the driest of sites. Faster growth and its greater resistance to littleleaf disease (a root rot associated with eroded, heavy clay soils and a fungus (*Phytophora cinnamoni*)) made loblolly preferable for plantations in the Piedmont (Belanger and others 1986). The earliest plantations were planted on old fields and represented only a small portion of the loblolly pine ecosystem (Boyce and others 1975). Over the past 50 years, increases in plantation acreage have generally mirrored declines in natural pine acreage. Today, plantations occupy a similar acreage in the Piedmont and Coastal Plain to that occupied by natural pine stands (Conner and Hartsell 2002).

The loss of topsoil during decades of row-crop agriculture greatly lessened the capacity of Piedmont soils to produce biomass. Coile (1948) noted that site index for shortleaf and loblolly pine declined markedly with decreases in topsoil thickness in the Piedmont. We suspect that site quality for loblolly pine may have decreased by as much as 20 points where 10 or more inches of topsoil were lost to

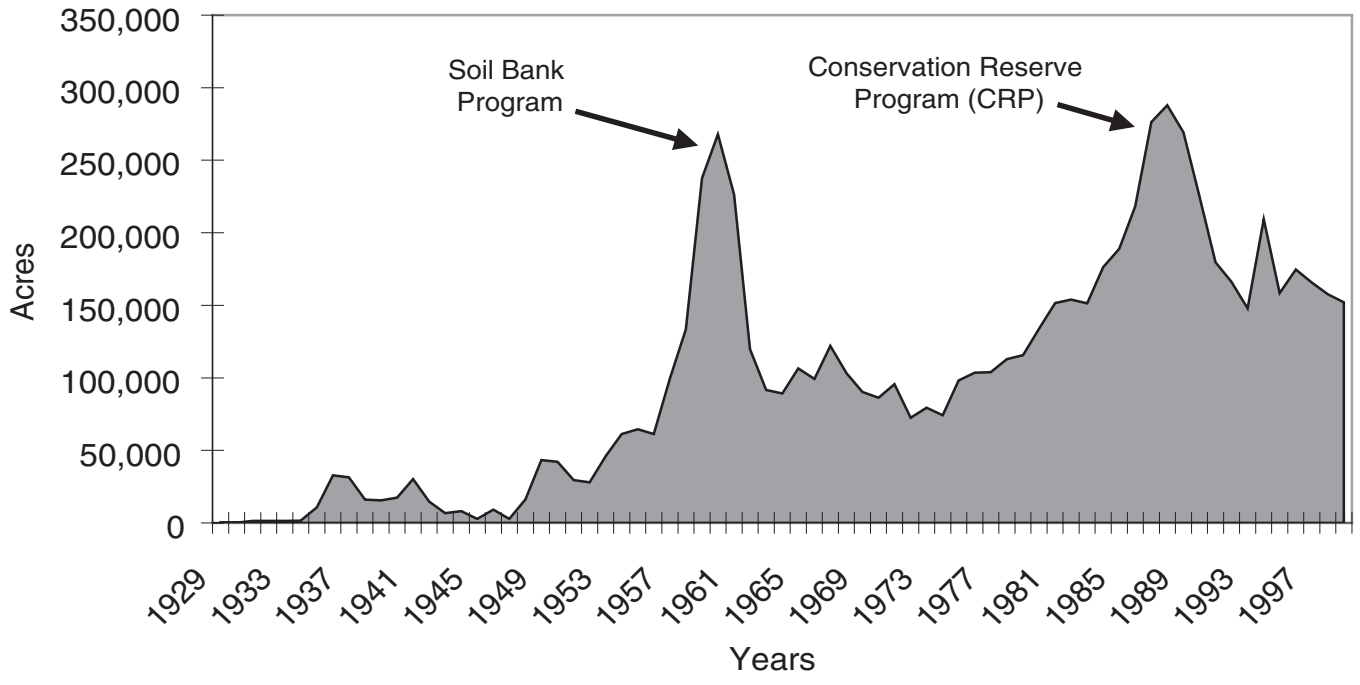

Figure 1—Acreage of planted seedlings per year in South Carolina from 1929 —to 2001.

erosion. Forestry also changed the Piedmont landscape through its fire suppression activities (Healy 1985). From the early decades of the 20th century, the USDA Forest Service and State forestry commissions sought to exclude wildfire from the landscape. They were quite successful, and the removal of fire allowed hardwood understories to encroach into both natural and plantation pine stands on lands not being farmed. Thus, open, fire-maintained stands (of both pines and hardwoods) became only a memory as fire exclusion became the dominant policy for forestry agencies. Forest management in the Piedmont is now challenged by the rapid urban growth and associated sprawl of the region. According to Wear (2002), the human population in the Piedmont grew rapidly from 1990 to 1999 and already has a population density along the I-85 corridor exceeding that which is compatible with forestry. When population density approaches 75 people per square mile, there is a 50:50 chance of practicing forestry. When population density exceeds 150 per square mile, the chance approaches zero. Because of the area's high population density, it is certain that a different kind of forestry will have to be practiced in many parts of the Piedmont if forestry is to be practiced at all.

The Southern Pine Beetle

Although there have been a number of SPB outbreaks in the Piedmont over the past 60 years, the recent epidemic that began in the late 1990s is by far the worst. In South Carolina, North Carolina, and Georgia, millions of dollars of damage have occurred as the beetles worked their way through drought-stressed pines growing in generally dense stands. Pine plantations have increased dramatically over the decades, adding to the acreage of pine stands that become increasingly susceptible to SPB infestations as they age and become stressed under droughty conditions. As often the case with serious outbreaks of SPB, the current outbreak is associated with a severe drought that has affected the entire South for the past 5 years, especially the upper Piedmont of the Carolinas and Georgia. Drought intensifies the stress that dense plantations already face on eroded Piedmont soils. Forest entomologists have known for decades that stressed trees are more prone to beetle attacks (Thatcher and Conner 1985), and foresters have long known that poor sites should support lower stocking to help alleviate this stress (Belanger 1980).

Oleoresin (sap) production is a primary defense mechanism of pine trees against SPB attack. SPBs are attracted to stressed pine trees, which are poor oleoresin producers (Hodges and Lorio 1975, Matson and others 1987). Beetles disproportionately attack and overcome over-mature trees of low vigor, although in epidemic populations they will attack dense stands of young trees (Hedden and Belanger 1985). During periods of drought, dense stands of pine trees are more stressed, and the probability of epidemic infestations by southern pine beetles is increased.

Both natural stands and plantations have been hit hard by SPB during the recent drought. In South Carolina alone, damage from the current beetle outbreak exceeded 75 million dollars in 2001 (http://www.state.sc.us/forest/). Few stands of any pine species are immune from attack when the SPB reaches epidemic populations. Beetle outbreaks in loblolly, shortleaf, Virginia, and white pine (*P. strobus*) have been witnessed on the Clemson Experimental Forest in the South Carolina Piedmont during the recent epidemic.

Management Implications

The land-use history of the Piedmont and current knowledge about the SPB provide insights concerning future management options to restore health to Piedmont pine forests. It is evident that present forest stands and landscapes are drastically different from those of previous millennia. Because of frequent fire, stand densities would have been much lower, understories would have been open, and soil moisture and nutrients would have been supplied in greater quantities to individual trees because there were fewer of them. The obvious implication of the Piedmont's land-use history and our current knowledge about SPB is that today's pine plantations are much too densely stocked. The dense stocking of pine trees increases moisture and nutrient stress on sites abused by agricultural practices for over 100 years and far exceeds stand densities during previous millennia of Native American occupancy. The increased probability that SPBs will damage or destroy pine stands, coupled with currently depressed smallwood markets, serves as a disincentive for landowners to invest in expensive reforestation. Restoring the health of Piedmont pine forests will require active management and greater consideration given to relations between stand stocking levels and soil capability. Current growth and yield models used to maximize wood production are counter productive if they encourage beetle outbreaks at some point during the rotation. A new model based on a balance between restoring forest health (encouraging plant/animal diversity and reducing susceptibility to damage from forest pests) and sustaining production of high-value wood products is needed. Enhanced aesthetic quality would be an associated value with this new vision of forestry.

Tree Spacing and Intermediate Treatments

Newly established plantations should either be planted at much wider spacing, e.g., 12 by 12 feet, or planted at current spacings and thinned early (by age 15 to 18) and frequently (every 5 to 7 years) thereafter. The latter alternative is probably best, because widely spaced trees develop rapid bole taper and are poor pruners, which degrades log quality (Schultz 1997). Burton (1982) showed that early, heavy thinnings combined with pruning of green limbs and understory control could produce good quality sawlogs in a much shorter time than conventional thinning regimes.

Where prescribed fire can be used, burning should be conducted at about 3-to 5- year intervals after trees are large enough to be safely burned (Van Lear and Waldrop 1991). Burning should precede a thinning by 1 or 2 years to reduce the risk of damage to crop trees from intense fire in the downed tops of thinned trees. During periods of drought, burning should be conducted with great care, if at all, to avoid stressing trees even more. If burning is not feasible, herbicides can be used to control understory encroachment of hardwoods; this can also improve habitat for some wildlife species (Wigley and others 2002). In certain cases, herbicides and fire can be used together to

accomplish management objectives. The goal should be to favor vigorous, high-quality trees in relatively open stands as the rotation proceeds. Such stands would not only be more resistant to SPBs, but would also be aesthetically attractive and excellent wildlife habitat for those species that prefer open woodland conditions. The property value of such sites should far exceed that of land supporting dense plantations.

To restore forest health, residual basal areas following thinnings should be lower than those currently recommended for maximum timber production for both even and uneven-aged stands. Depending on site quality, target basal areas for even-aged stands should be in the range of 50 to 70 square feet per acre late in the rotation, although early thinnings should not remove more than about 40 percent of the stand's basal area to minimize damage from potential ice or wind storms or both. For uneven-aged management, stand density should be maintained at levels that allow regeneration to occur in openings created by periodic removal of small groups of trees. Actively managed, fully stocked uneven-aged stands of loblolly pine will have considerably less basal area than fully stocked even-aged stands (Schultz 1997).

First thinnings have recently become a management problem because of lack of markets for small wood. However, as engineered wood technology emerges and wood energy becomes more cost effective, small wood markets should improve. A diversity of competitive markets is necessary to allow forest landowners to keep their stands healthy and reduce the likelihood of SPB infestations. Pruning of crop trees should be considered, especially on good quality sites where rapid volume growth will help offset costs of pruning. Pruning increases diameter growth at the base of the crown, making the stem more cylindrical and increasing its volume (Schultz 1997).

Harvesting/Site Quality Relationships

The length of time that trees can be grown and remain vigorous and healthy depends on site quality. Over-mature stands of pines should be avoided. Stands should be harvested when they reach financial maturity, which will vary with the type of product being produced and site quality. On eroded Piedmont sites, loblolly pine trees over 50 years grow slowly and become susceptible to SPB attack. Pine trees will remain vigorous on better quality sites at older ages and may be more resistant to SPB attack, although when the beetles are in epidemic populations they can overcome the defense mechanisms of younger stands (Personal communication. Steve Perry and Knight Cox, Forest Managers, Clemson Experimental Forest). Even-aged stands of loblolly pine must be thinned on schedule and harvested prior to the loss of tree vigor.

Uneven-aged management of loblolly pine is rarely used in the Piedmont today but perhaps should be given another look in light of recent SPB outbreaks. A stand's vulnerability to complete destruction by fire, bad weather, or biotic agents is less than with uneven-age management (Schultz 1997). In fully stocked, uneven-aged stands, about two-thirds to three-fourths of the basal area will be in sawlogs (Farrar 1981). Thus, managed uneven-aged stands have higher lumber yields in large, valuable stems because a greater proportion of the stand is in sawtimber. A major concern with uneven-age management is ensuring that regeneration develops following harvesting of small groups of trees. Regeneration normally develops following selection harvest if pine overstory density is less than 50 square feet per acre and site conditions are favorable (Schultz 1997). Prescribed burning must be used carefully with uneven-aged management because the fire regime that controls understory hardwoods and maintains open-stand conditions can destroy vulnerable age classes of pine. In many cases, herbicides may have to be used to control aggressive hardwoods where fire cannot be used.

Foresters and landowners should consider the larger landscape when they are deciding how to manage their forests. A healthy landscape composed of a range of seral stages in both pine and hardwood types, with generally lower densities in all stages, would theoretically enhance tree and stand vigor and reduce infestations of SPBs. Active even-age and uneven-age management of pine stands using thinnings, frequent prescribed burns or herbicides where burning is not feasible, and timely harvests to remove over-mature trees or stands, would maintain open park-like conditions while producing high-quality timber for lumber, poles, veneer logs, etc. Stringers of hardwood stands or mixed pine-hardwood stands on more mesic sites would enhance environmental qualities of the landscape and break up the continuity of pine stands, thereby lessening potential outbreaks of the SPB.

CONCLUSIONS

1. Forests in the Piedmont were maintained for millennia in an open condition by anthropogenic- and lightning-ignited fires.
2. Piedmont soils were extensively eroded during the era of row-crop agriculture, making soils in the region less capable of supplying moisture and nutrients during drought periods.
3. Unmanaged, overstocked pine stands established either naturally or by planting over the past 70 years have fueled the current SPB epidemic and resulted in millions of dollars in damage.
4. Beetle-damaged stands and depressed smallwood markets currently serve as a disincentive to invest in expensive reforestation.
5. Prescribed burning or herbicide applications where burning is not feasible, along with frequent thinnings and timely harvests, should be used to maintain open stands and encourage herbaceous vegetation.
6. A Piedmont forest landscape consisting of a shifting mosaic of low-density pine stands in all seral stages, intermixed with hardwood and pine-hardwood stands, should reduce the intensity of future SPB outbreaks and provide the commodity and non-commodity values desired by landowners and society.

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RELATIVE IMPACTS OF ICE STORMS ON LOBLOLLY PINE PLANTATIONS IN CENTRAL ARKANSAS

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Abstract—Catastrophic ice storms can inflict widespread damage to forests in the Southeastern United States. Two severe ice storms struck Arkansas in December 2000, resulting in heavy losses to loblolly pine (*Pinus taeda* L.) plantations. We assessed the type and magnitude of damage in four loblolly pine plantation conditions: unthinned 11- to 12-year-old stands, once-thinned 18- to 19-year-old stands, twice-thinned 24- to 25-year-old stands, and at least twice-thinned > 28-year-old stands. Each condition was replicated three times on similar sites. Patterns in tree damage extent and type were apparent between plantations of different ages and thinning histories. The oldest plantations had the greatest proportion of undamaged survivors, while the youngest stands received the highest injury. Young loblolly pines suffered from bent stems more often than trees in older plantations. Loblolly pines in the oldest plantations were virtually immune to stem damage yet experienced frequent crown and branch loss. Intermediate-aged plantations had somewhat more stem breakage and uprooting than either younger or older pine plantations. Differences in the degree and type of damage were closely related to tree size and stand attributes. Logistic regression models were also developed to predict severe damage probability from stem diameter and tree density.

INTRODUCTION

Ice storms are some of the most catastrophic disturbances in southern forest lands. At least a portion of the region is affected by glazing every year, and some events are truly monumental, covering millions of acres and inflicting many millions of dollars in damage; e.g., Fountain and Burnett 1979, Halverson and Guldin 1995, White 1944.

Pine plantations can be particularly vulnerable to ice damage, especially when storms coincide with thinning operations (Hebb 1973, Nelson 1951). Thinning removes much of the structural support that comes from the close proximity of trees in unthinned stands. Recently exposed pines also tend to be spindly, with relatively thin, weak stems and most ice-accumulating surfaces; e.g., branches, foliage, found in the crown of the tree (Bragg and others, in press).

Two severe ice storms struck Arkansas in December 2000, with especially heavy damage inflicted on recently thinned loblolly pine (*Pinus taeda* L.) plantations. It became apparent in the weeks following these ice storms that not all plantations responded similarly to the glaze events. Since these differences may affect their poststorm management, we quantitatively evaluated the aftermath. This paper reports on a study that compared the type of injury and relative extent of glaze damage for loblolly pine plantations in central Arkansas.

METHODS

December 2000 Arkansas Ice Storms

National Oceanic and Atmospheric Administration records show that the first ice storm began on December 12, 2000, and deposited up to 2 inches of ice before ending on December 13 (National Oceanic and Atmospheric Administration 2001). A second ice storm began on December 25 and continued until December 28, with accumulations approaching 3 inches in western Arkansas. Local observers attributed the majority of the damage in central Arkansas to the first glaze storm. No site-specific measurements of ice accumulation are available, but judging from the damage witnessed in central Arkansas, the region probably received 1 to 2 inches of ice in the first storm and perhaps 0.5 to 1 inch from the second.

Study Sites

Twelve study sites were located on International Paper Company property in Dallas County, AR. Loblolly pine plantations were chosen on the basis of their age and thinning history. Four distinct age and thinning combinations consistent with the management strategies of the cooperating timber company were selected to represent important developmental stages. These combinations consisted of three replicates each of stands that were 11 to 12 years old, unthinned; 18 to 19 years old, once-thinned; 24 to 25 years old, twice-thinned; and > 28 years old, at least twice-thinned.

Field Sampling

Field work began in early March of 2001 and ended approximately 1 month later. Resource constraints prevented sampling any sooner, which may pose some problems in damage assessment because of the potential for recovery of injured trees. For example, pines that are bent by snow or ice can quickly straighten (Kuprionis 1970). However, we did not expect major discrepancies due to recovery between December and April because the winter of 2000-01 was particularly cold, and straightening usually occurs only in small-diameter trees after the growing season has begun.

Each of the 12 stands identified as likely candidates was further subsampled with 3 measurement subplots randomly located from a starting point placed to keep the plots within the stand. These three subplots were averaged to produce a composite value for each replicate, which were then

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

tested for their significance. Two subplot sizes were used to reduce the amount of necessary sampling: 0.10-acre circular subplots were used in the 11- to 12- and 18- to 19-year-old stands, while the 24- to 25- and >28-year-old stands were surveyed using 0.25-acre circular subplots. Within each subplot, every merchantable-sized [> 3.5 inches diameter at breast height (d.b.h.)] loblolly pine living at the time of the ice storm was measured to the nearest 0.1-inch d.b.h. and assigned to a damage class (fig. 1). Damage types included apparently undamaged, branch loss (as a percent of total live crown), crown loss (loss of growing tip with some live branches remaining, as a percent of total live crown), stem breakage (bole breakage below the live crown), stem bending (bent stem, root system intact), and uprooting (bent stem, root system broken). Most individuals only had one type of damage reported; however, some had multiple injury types. For example, a tree may experience both branch loss and bole bending. Any mitigating circumstances, such as stem defects, forks, or damage from a neighboring tree, associated with a tree's damage were also recorded.

Statistical Analysis

Differences in stocking and size distribution required that damage comparisons between stand-age classes be performed using relative (percent) information. All percentage (p) data were adjusted using the arcsine transformation ($p' = \arcsin\sqrt{p}$) (Zar 1984). If the adjusted data still experienced major heterogeneity of variance, then an additional log transformation [$p'' = \log(p'+1)$] was performed before significance was determined using Tukey's honestly significant difference test ($\alpha = 0.05$). However, all values are reported in the tables and text as untransformed percentages.

Models to predict the type of damage were also developed for pines with major or critical damage. This approach has been previously used to predict ice damage to individual trees (Amateis and Burkhart 1996, Cain and Shelton 2002). Using a backward elimination procedure ($\alpha = 0.05$), the following were fit with logistic regression (SAS Institute 1990):

$$P_B = \frac{\exp(a_B + bD + cT)}{1 + \exp(a_B + bD + cT)} \quad (1)$$

$$P_C = \frac{\exp(a_C + bD + cT)}{1 + \exp(a_C + bD + cT)} - P_B \quad (2)$$

$$P_R = \frac{\exp(a_R + bD + cT)}{1 + \exp(a_R + bD + cT)} - P_B - P_C \quad (3)$$

$$P_S = 1 - P_B - P_C - P_R \quad (4)$$

where

a_i and P_i = the intercept and probability of the i^{th} damage type (B = stem bending, C = crown damage, R = root sprung, and S = stem breakage)
D = d.b.h. (inches)
T = trees per acre
b and c = fitted coefficients.

If a pine had more than one type of damage, only the most severe injury was used. Stand basal area and plantation age were initially included in the full model but were

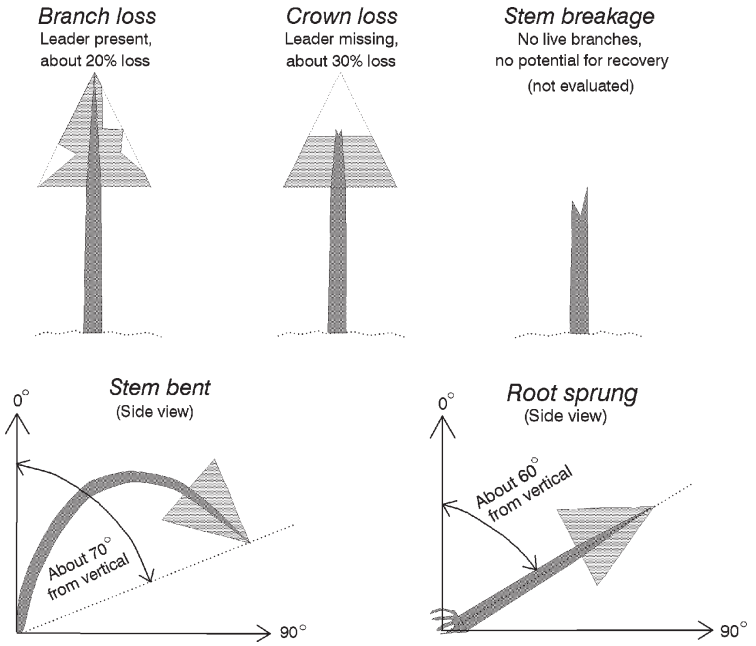

Figure 1—Classes of ice storm damage and measurement technique.

removed from the final equations because their coefficients were not significant.

RESULTS AND DISCUSSION

Stand Conditions

Table 1 contains the summary statistics of the age classes. More than 1,250 loblolly pines ranging from 5 to 13 inches d.b.h. were measured, with 1,125 (90 percent) having some measurable damage. Not surprisingly, the youngest, unthinned plantations had the highest and most variable pine densities, and the oldest (at least twice-thinned) plantations had the lowest and least variable number of stems. Mean pine d.b.h. also increased with stand age, from 5.4 inches in the 11- to 12-year-old plantations to 12.2 inches in the > 28-year-old stands. Basal area declined as the stands matured and were thinned, from an average of almost 105 square feet per acre in the youngest plantation to about 66 square feet per acre in the plantations older than 24 years. These statistics correspond to the loblolly pine plantation management strategy of the corporate landowner in Arkansas, in which plantations are carefully thinned to regulate growth and yield before being clearcut by age 35 years and replanted.

Table 1—Summary statistics of the loblolly pine plantations reported in this study following the December 2000 Arkansas ice storms

	Plantation age class (years)			
Stand attribute[a]	11 – 12	18 – 19	24 – 25	> 28
	trees per acre			
Pine density				
Minimum	330	130	84	68
Maximum	980	370	216	104
Average	640	214	135	81
Standard deviation	185.9	85.3	48.6	11.0
	inches			
Mean pine d.b.h.				
Minimum	5.0	7.5	6.8	11.7
Maximum	5.9	9.6	11.6	13.0
Average	5.4	8.3	9.4	12.2
Standard deviation	0.29	0.63	1.75	0.46
	square feet per acre			
Basal area				
Minimum	52.8	56.7	49.1	60.1
Maximum	142.7	139.8	77.9	82.6
Average	104.8	83.1	64.9	67.3
Standard deviation	29.96	31.75	9.18	6.97

[a] Stand attribute ranges and means are determined from the nine subplots per plantation age class (three subplots per replicate x three replicates). A total of 1,255 loblolly pine trees were measured across all treatments.

Damage Patterns

Loblolly pine plantations of different age and thinning histories experienced significant differences in their response to ice accumulation. The oldest plantations in our study had the trees with lowest levels of damage, while the youngest stands had the highest proportion of injured pines (table 2). Of the pines in the 11- to 12-year-old age classes, < 1 percent escaped the 2000 ice storms with no apparent damage, rising to > 11 percent in the 18- to 19-year-old stands, almost 16 percent by ages 24 to 25 years, and > 40 percent in the > 28-year-old plantations.

The type of damage inflicted on each plantation age class depended on the size of the trees involved. A strong correlation between stand age and diameter was apparent in these managed even-aged stands. Other researchers have noted different types of damage corresponding to tree size; e.g., Burton 1981, Buttrick 1922, Downs 1943, Kuprionis 1970. In natural, even-aged loblolly pine stands, Cain and Shelton (2002) reported more crown damage from an ice storm but less stem breakage than we observed. Assuming no confounding factors like disease, extreme site conditions, or high winds in conjunction with the glazing, variation in damage type was probably a function of bole pliability and crown surface area. Thus, the smallest loblolly pines were much more likely to severely bend when loaded with ice, while those of intermediate sizes experienced both bending and stem breakage, and the largest pines suffered very little bending or breakage (tables 2 and 3). Given the classes in table 2, virtually no statistically significant differences appeared in the extent of damage experienced by pines in the 18- to 19- and 24- to 25-year-old plantations. However, the greater number of smaller diameter pines in the 18- to 19-year-old plantations meant that more pronounced stem bending occurred (tables 2 and 3). These intermediate-sized trees are usually considered the most vulnerable to ice storms because they

Table 2—Comparison of loblolly pine plantation response to glazing from the December 2000 ice storms in central Arkansas

	Plantation age class (years)			
Damage type	11 – 12	18 – 19	24 – 25	> 28
	percent[a]			
Undamaged pines	0.7 a	11.4 b	15.8 b	40.8 c
Pines with branch damage	1.8 a	15.3 b	7.2 ab	37.9 c
Pines with crown damage	11.5 a	11.3 a	11.6 a	17.5 a
Pines with broken boles	1.8 a	14.6 a	8.7 a	3.8 a
Pines with bent boles	87.5 a	60.6 b	62.6 b	0.0 c
Rootsprung pines	2.2 a	1.1 a	4.7 a	0.0 a

[a] Row means with the same letter are not significantly different at $\alpha = 0.05$. Column totals may not sum to 100 percent because multiple damage types were recorded on some trees; e.g., branch loss and bole bending.

Table 3—Distribution of ice damage level by d.b.h. class for branch breakage, bole breakage, and bole bending plus uprooting from the December 2000 Arkansas ice storms

Damage type and level	D.b.h. class (inches)					
	< 7	7 – 10	> 10	< 7	7 – 10	> 10
	count			*percent*		
Branch loss						
Insignificant	7	16	65	70.0	55.2	69.9
Minor	1	12	25	10.0	41.4	26.9
Moderate	2	1	3	20.0	3.4	3.2
Major	0	0	0	0.0	0.0	0.0
Critical	0	0	0	0.0	0.0	0.0
Crown loss						
Insignificant	4	2	15	6.8	4.7	30.6
Minor	14	23	23	23.7	53.5	46.9
Moderate	14	9	4	23.7	20.9	8.2
Major	11	5	5	18.6	11.6	10.2
Critical	16	4	2	27.1	9.3	4.1
Bending/root sprung						
Insignificant	25	36	26	4.4	18.7	32.1
Minor	75	50	38	13.2	25.9	46.9
Moderate	218	48	13	38.4	24.9	16.0
Major	108	21	1	19.0	10.9	1.2
Critical	142	38	3	25.0	19.7	3.7

Insignificant = > 0 to < 10 percent branch or crown loss, > 0 to < 10 degree bend; minor = 10 to 24 percent branch or crown loss, 10 to 19 degree bend; moderate = 25 to 44 percent branch or crown loss, 20 to 39 degree bend; major = 45 to 69 percent branch or crown loss, 40 to 59 degree bend; critical = 70 to 100 percent branch or crown loss, > 60 degree bend, or root sprung.

often do not recover fully from severe bending, and many will experience lethal levels of crown damage and bole breakage (Downs 1943, Kuprionis 1970).

Larger loblolly pines experienced more crown damage and significantly greater branch loss than smaller size classes. Greater resistance to bending or breakage under mechanical loads is observed for larger diameter cantilevered beams (Cannell and Morgan 1989). There appeared to be less uprooting of larger pines in the stands sampled for this study, although at other locations we observed root failure in even bigger trees. Tip-over was uncommon in our study area because of the deep, relatively dry soils and the lack of strong winds associated with this ice storm.

Logistic Damage Models

Fitted coefficients for predicting trees with major or critical damage (see footnote of table 3 for damage class thresholds) can be found in table 4, and the probabilities of a particular type of damage occurring are plotted in figure 2. Even though the models did not explain much of the variance in the data (R^2 = 0.26), model concordance (78.3 percent) and discordance (21.5 percent, with 0.2 percent in ties) were fairly good.

The most prevalent types of major and critical damage were stem bending and breakage. Stem bending was more prevalent in trees with smaller diameters, while stem breakage was more common with the larger trees. An increase in trees per acre caused a slight increase in the probability of stem bending with a concomitant decrease in the probability of stem breakage. The greater number of neighboring trees probably provided support for bending stems, thus preventing individuals from exceeding their failure thresholds.

Pines with major or critical damage had approximately equal probabilities (about 0.15) of having crown damage or being root sprung. These types of damage were most common in trees near the middle of the d.b.h. range, and increases in tree density caused a slight shift in peak probability from smaller to larger trees. In 13- to 18-year-old natural loblolly pine stands, Cain and Shelton (2002)

Table 4—Logistic regression model results to predict glaze injury type in heavily damaged loblolly pine plantations in Arkansas following the December 2000 ice storms

Parameter	Parameter estimate	Standard error of estimate	Wald chi-square	Prob. > chi-square
a_B	2.8197	0.5608	25.3	0.0001
a_C	3.4506	0.5716	36.4	0.0001
a_R	4.0142	0.5843	47.2	0.0001
b	-0.4706	0.0667	49.7	0.0001
c	0.0019	0.0005	13.3	0.0003

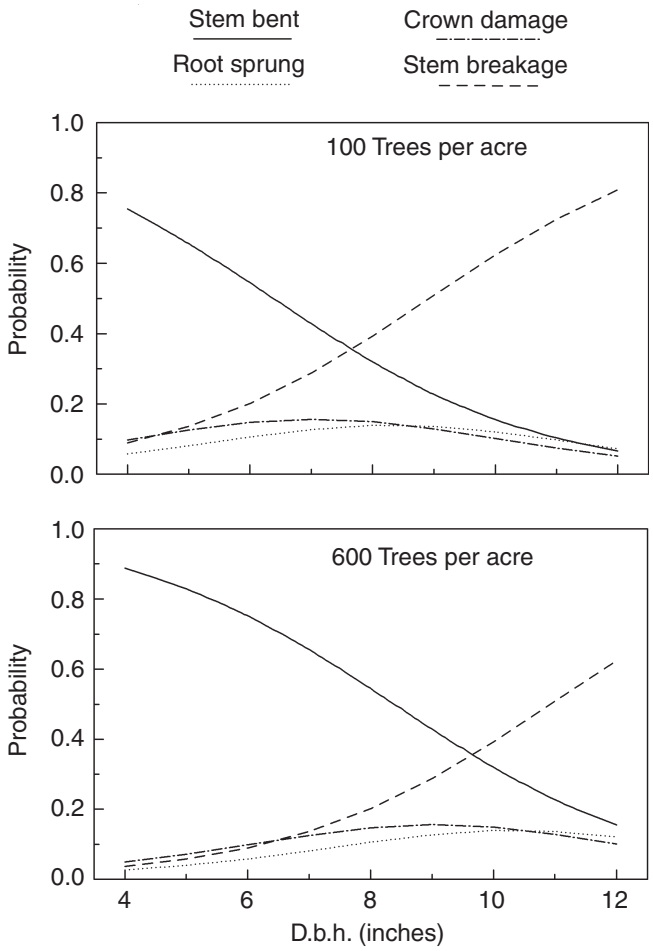

Figure 2—Logistic regression results for ice-damaged loblolly pine plantations in Arkansas, assuming 100 and 600 trees per acre. The curves follow the probability of a tree of a given d.b.h. with major or critical damage classifying into a particular damage type.

similarly found that d.b.h. and stand basal area affected the type of tree damage resulting from an ice storm.

Fourteen percent of the pines with major or critical levels of injury and 10 percent of the root-sprung trees were classified as having damage associated with a neighboring tree. Thirteen percent of the trees with crown damage had forked main stems, compared with 3 percent of the trees with bent stems. Only 1 percent of the trees with major or critical damage was classified as having damage associated with a bole defect, such as cankers from fusiform rust (*Cronartium fusiforme* Hedg. & Hunt).

CONCLUSIONS

As many have reported before, southern pine plantations are susceptible to heavy damage from ice storms. This study provided further confirmation of the relationship between tree size and damage extent and type. Our results support Zeide and Sharer's (2002) assertion that one of the best defenses against glaze damage is to grow trees out of the vulnerable size range as quickly as possible. Determining the appropriate planting density and thinning regime is critical to producing individuals capable of weathering an ice storm.

Combined with other research on glazing, this work also has implications for salvage following severe ice storms. Since a large portion of major or critically injured loblolly pines die within the first growing season (Bragg and others 2002, Kuprionis 1970), salvage efforts should focus on the intermediate-aged stands that suffered the greatest proportion of severe damage. Younger and older plantations probably did not experience sufficient levels of permanent damage to warrant immediate salvage efforts, although some remediation may be needed to minimize fire danger and insect outbreaks.

ACKNOWLEDGMENTS

We thank Karl Hansen, Alan Jenkins, and International Paper Company for their assistance in locating study sites and allowing us to sample them. Adrian Grell, Curtis VanderSchaaf, David Higgins, and Bruce Walsh helped with the field work. Michael Cain, Paul Doruska, and Karl Hansen graciously provided reviews of this paper. Financial and logistical support was provided by International Paper Company; the U.S. Department of Agriculture Forest Service, Southern Research Station; and the Arkansas Forest Resources Center.

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IMPACTS OF INSECT DEFOLIATION IN COTTONWOOD PLANTATIONS IN MISSISSIPPI

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Abstract—In spring 2001, a notodontid moth, *Gluphisia septentrionis* Wlkr., defoliated about 2,000 acres of 9- and 10-year-old eastern cottonwood (*Populus deltoides* Bartr.) trees in west-central Mississippi. The farm manager had never seen cottonwood defoliated by that species of moth, because it was not considered a pest in Mississippi. When the trees leafed out again, cottonwood leaf beetles (*Chrysomela scripta* F.) attacked them. In order to avoid two defoliations by mid-season, the manager applied an insecticide. Cottonwood leaf beetles commonly attack young *Populus* but seldom require treatment in trees > 2 years old. However, this defoliation by the *Gluphisia* moth caused a flush of leaves in mid-season when cottonwood leaf beetle populations were high. Cottonwood growth is indeterminate, so the timing of insect defoliations can have a variety of effects on growth and energy storage. In spring 2002, *G. septentrionis* larvae were present in the same stands and again caused defoliation. This paper considers tree mortality and growth after 2 years of defoliation, as well as some associated economic effects.

INTRODUCTION

In mid-May 2001, partial defoliation of eastern cottonwood (*Populus deltoides* Bartr.) trees occurred in 9- and 10-year-old plantations that are part of a 15,000-acre tract in Issaquena County, MS, which is used for recreation and industrial production of cottonwood fiber. Trees were being defoliated from the top down, and after the felling of several trees, many larvae were discovered of the notodontid moth *Gluphisia septentrionis*. Surveys were begun, but within 2 weeks approximately 2,000 acres in the northern part of the tract had been completely defoliated. The farm manager reported she had not seen cottonwood defoliated previously by *Gluphisia* and wanted to know if this was a single event or if there would be successive generations that might require management. *G. septentrionis* was not considered a common pest in Mississippi (Morris and Oliveria 1976, Morris and others 1975); the literature suggested that two generations were possible (Baker 1972). The manager decided to set out a light trap and evaluate the next generation of adults. A few days later, we observed several small wasps ovipositing into large *Gluphisia* larvae. Inspecting a freshly felled tree, we found 14 clusters of pupae of the parasitoid *Eulophus orgyiae* within a few minutes. Would the parasitoid control the next generation of *Gluphisia*? Unfortunately, that question would remain unanswered, because when the trees refoliated that season, cottonwood leaf beetles (*Chrysomela scripta* F.) attacked them, and the manager opted for chemical control rather than suffer two defoliations by mid-season. The cottonwood leaf beetle is a common pest of young *Populus,* but trees > 2 years old seldom require treatment. In this case, we believe the defoliation by *Gluphisia* caused the growth of new, attractive leaves in mid-season, when cottonwood leaf beetle populations were quite high. Although it was not present later in 2001, *G. septentrionis* reappeared in the same stands in May 2002. It again caused nearly complete defoliation of the cottonwoods but did not appear to have spread to neighboring stands. The farm manager did not apply chemical control but accelerated harvest in some of the affected stands as a result of her concerns about increased mortality and loss of growth after 2 years of defoliation.

The common *Gluphisi*a feeds on various poplars, especially trembling aspen (*P. tremuloides* Michx.) (Baker 1972, Wagner and others 1997). Adult moths emerge in June and have a wingspan of about 1.25 inches. The front wings are gray with irregularly shaped beige and dark gray bands; the hind wings are uniformly light gray (Ives and Wong 1988). Mature larvae are about 1.5 inches long, pale green with yellow subdorsal stripes, and have pinkish-to-reddish spots on the back (Baker 1972, Wagner and others 1997). The common *Gluphisia* was reported by Baker (1972) to occur in Southeastern Canada and parts of the Northeastern United States. An Internet search revealed a wider distribution within the continental United States, as reported by the U.S. Geological Survey, Northern Prairie Wildlife Research Center at www.npwrc.usgs.gov/resource/distr/lepid/moths/usa/694.htm . The distribution map at this Web site shows *G. septentrionis* as sporadically distributed from Maine to South Carolina in the East and from Oregon to California in the West, with occurrences in most other States. South Carolina and Louisiana each had confirmed records from one county, Arkansas had reports from two counties, and Mississippi had reports from six counties, including Warren County, which borders Issaquena County to the south. Another Web site listed the common *Gluphisia's* range from Nova Scotia to Florida and west to Texas, and recorded a collection in Georgia (Adams 2002). While Baker's book (1972) focused on insects in forests of the Eastern United States, it appears either that he was unaware of records outside the Northeast, or that the range of *G. septentrionis* has expanded over the last 30 years. Regardless, we undertook the present study to document occurrence of this defoliator on cottonwood trees in Mississippi, and to determine if complete defoliations in

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

consecutive years would affect cottonwood growth and mortality.

METHODS

In fall 2002, we selected three stands within the estimated 2,000-acre area affected by *G. septentrionis* defoliations in spring 2001 and 2002. Our intent was to estimate mortality and collect increment cores for the purpose of measuring annual growth. Stands averaging in size from 50 to 80 acres were planted in 1992 or 1993, making them either 9 or 10 years old during the first defoliation in 2001. Cottonwood trees had been planted at 12- by 12-foot spacing. A tree in two stands was completely defoliated in 2001 and 2002, and in one defoliated stand every other row of trees was removed in 2000, resulting in a spacing of 12 by 24 feet. The third stand was not defoliated in either 2001 or 2002. We sampled tree condition (either alive or dead) in each stand by evaluating 50 trees per row in each of 10 rows. Sample rows were systematically selected and equally distributed throughout each stand. A special category of live trees, those with live stems but dead crowns, was counted in all stands. Missing trees were not tallied, but the next standing tree in the row was. As many as five different clones of eastern cottonwood may have been planted in each of the three stands, and different clones would have been randomly mixed throughout each (Personal communication. 2003. Jackie Henne-Kerr, Manager, Vicksburg Procurement, Tembec U.S.A. LLC, Vicksburg, MS 39183). It was impossible to measure the effect of defoliation on different cottonwood clones because they were mixed in the stand. The average number of dead trees and trees with dead stems and live crowns were compared between site types using chi-square tests (Ott 1977).

We measured tree growth on 1 increment core removed from each of 23 trees per stand type using a Swedish increment borer. Sample trees were cored at the same time tree conditions were evaluated. Sample trees were selected systematically so that they were equally distributed throughout each stand. Increment cores were glued into grooves in wooden blocks, and growth-ring surfaces were prepared for measurement by sanding them with progressively finer grain sand paper. Annual increments for each of 9 or 10 years were measured to the nearest 0.001 mm using a dendrochronometer. Annual growth averages were calculated from the cores collected for each stand type, plotted against time, and examined for differences in growth rates. Each tree from which an increment core was removed was measured for total height and diameter at breast height (d.b.h.). Heights were measured to the nearest 0.1 foot with the aid of a digital hypsometer; diameters were measured to the nearest 0.1 inch using a metal diameter tape. T-tests were used to compare average heights and diameters among site types.

RESULTS AND DISCUSSION

About 2,000 acres of cottonwoods had been defoliated by *G. septentrionis* in the spring of 2001 and again in spring 2002. Large numbers of parasitoids, *E. orygiae*, were documented following the *Gluphisia* population in spring 2001. Presumably, they might have controlled the *Gluphisia,* as in standard predator-prey models. The *Gluphisia* defoliation forced the trees to produce new leaves during the summer, which were attractive to the cottonwood leaf beetle (*C. scripta*). Rather than suffer two or more defoliations in one growing season, the manager chose to treat the leaf beetle infestation with an insecticide. Her decision to spray the insecticide followed consideration of the many biological and economic factors involved. The decision to spray probably was not economically sound, although she had an obligation to keep her company's paper mill supplied with wood chips. For a large corporation with a mill, losses due to a pesticide application might be recovered through sales of paper products, but this probably will not be the case for an owner of a small tree farm whose only source of income is the narrow profit margin from selling cut trees, as the following example will show.

There were no economic injury levels or thresholds for treatment to consult for *Gluphisia* in cottonwood plantations. In the South*, Gluphisia* has multiple generations, and the trees were defoliated early in the season. Parasitoids were observed but could not be relied on to suppress the population. The first economic question was, How much does a treatment cost? This plantation included a nursery that was treated with insecticides on a regular basis, so it was determined the trees could be sprayed for $8.00 per acre. The second question was, Is $8.00 per acre economically feasible? To answer that question, the value of the crop had to be considered. Cottonwood is one of the fastest growing hardwood trees in North America. In the South, it is grown for pulp and normally harvested after about 10 years. An excellent yield is 60 tons per acre, and the product sells today for $10.00 per ton. On this site the expected yields were between 35 and 40 tons per acre, or $350 to $400. Plantation establishment and silvicultural practices cost about 50 percent of the harvested value ($175 to $200 per acre), over and above the land or rental cost (Stanturf and Portwood 1999). Eight dollars per acre is 40 percent of the profit for 1 year, but such cost should be considered in terms of the tree growth that will result from the treatment. Although the manager decided to spray before she considered growth and survival, she did evaluate those variables after the second defoliation in spring 2002.

Dead trees occurred at a rate of 7.3 percent in the two stands that were defoliated in 2001 and 2002, while 6.8 percent occurred in the nondefoliated stand (table 1). We could not determine the cause of death for each tree. Trees in both defoliated and nondefoliated stands had been killed or damaged by insects other than *G. septentrionis* or *C. scripta*, namely the poplar borer, *Saperda calcarata*. Chi-square tests showed no differences in the numbers of dead trees, or trees with live stems and dead crowns, between stands that were defoliated or not defoliated. In stands that were defoliated in 2001 and 2002, average height and d.b.h. were significantly greater than in the stand that was not defoliated either year (table 2). While an exhaustive survey and analysis of soil types was not done in the three stands, height and diameter growth of trees generally are known to be strongly influenced by soil texture and concentrations of nutrient elements. Stands that were defoliated presumably had higher growth rates because they were growing on more productive soils. These stands

Table 1—Numbers of live and dead cottonwood trees in samples taken within stands defoliated or not defoliated by *Gluphisia septentrionis* in 2001 and 2002 in Issaquena County, MS

Stand type		Trees		Live trunk/ dead crown
		Live	Dead	
	no.			
Not defoliated	500	466	34	3
Defoliated/50% cut	500	456	44	4
Defoliated	499	470	29	6
Total	1,499	1,392	107	13

Table 2—Average heights and diameters at breast height of cottonwood trees in samples taken within stands defoliated or not defoliated by *Gluphisia septentrionis* in 2001 and 2002 in Issaquena County, MS

Stand type		Average	
		Height[a]	Diameter[a]
	no.	*feet*	*inches*
Not defoliated	50	47.1 ± 1.15b	5.6 ± 0.18b
Defoliated/50% cut	50	56.0 ± 0.73a	7.4 ± 0.19a
Defoliated	50	56.9 ± 1.24a	6.8 ± 0.20a

[a] Different lowercase letters indicate results of T-tests (P = 0.05) showing differences in average heights and diameters between defoliated and nondefoliated cottonwoods.

all are within 5 to 10 miles of the Mississippi River, and the texture of soils there is highly variable. Figure 1 shows similar patterns of annual growth for the three stands, each of which had rapid growth during the first 5 years (about 8 mm or more per year) and much smaller growth (2 mm or less per year) for each of the last 3 years. Tree growth apparently was not influenced adversely by the *G. septentrionis* defoliation, because in 2001 and 2002 there were few differences in the average annual increments for defoliated and nondefoliated trees.

The similar growth rates indicate that two complete defoliations by *G. septentrionis* did not adversely affect tree physiology enough to reduce cottonwood growth. One reason for this is that *G. septentrionis* defoliated trees early in the growing season, thus allowing the trees sufficient time to produce a second set of leaves and replenish the storage chemicals used to make those leaves. Cottonwood in the Lower Mississippi Alluvial delta typically breaks bud in early April and holds its leaves into late October or early November. Complete defoliation by the common *Gluphisia* had occurred by the end of May in both years, which left at least 5 months per growing season for trees to replenish their carbon stores. In the Delta Experimental Forest near Stoneville, MS, and the Delta National Forest, near Rolling Fork, MS, Leininger and Solomon (1994) found a similar response to 3 years of heavy defoliation by the forest tent caterpillar (*Malacosoma disstria* Hübner) in sweetgum (*Liquidambar styraciflua* L.), green ash (*Fraxinus*

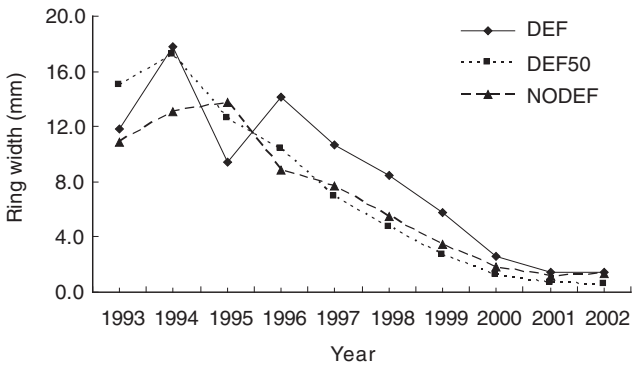

Figure 1—Average ring widths of cottonwood trees collected from stands that were defoliated (DEF) and nondefoliated (NODEF). A second stand with defoliated trees (DEF50) had every other row of trees harvested prior to defoliation. Annual averages are from the cores of 23 trees.

pennsylvanica Marsh.), water oak (*Quercus nigra* L.), overcup oak (*Q. lyrata* Walt.), Nuttall oak (*Q. nuttallii* Palmer), and willow oak (*Q. phellos* L.). While Leininger and Solomon reported small differences in ring widths and basal area indices for Nuttall and water oaks, they concluded that growth rates of all species damaged by the forest tent caterpillar recovered rapidly after an outbreak, and that individual tree crowns had recovered completely by the end of each growing season.

CONCLUSIONS

The farm manager decided to treat cottonwood plantations that had been defoliated by the common *Gluphisia* and the cottonwood leaf beetle during the first year of two consecutive defoliations. Although she chose to spray the affected stands, the presence of neither insect alone warranted treatment, nor was it necessarily economical. During the long Mississippi delta growing season, the cottonwood trees we studied did not suffer increased mortality or growth loss following successive early spring defoliations.

ACKNOWLEDGMENTS

The authors thank Emile Gardiner for telling us about the initial problem in the cottonwoods and coauthor Jackie Henne-Kerr who led discussions about cottonwood management. We thank Kevin Corbin and Steven Hughes for field work and tree ring collection, preparation, and analysis. We also thank Dan Wilson and Evan Nebeker for constructive reviews of the manuscript.

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IMPACTS OF OAK DECLINE ON FOREST STRUCTURE IN ARKANSAS AND OKLAHOMA: PRELIMINARY RESULTS

Eric Heitzman and James M. Guldin[1]

Abstract—We established field plots in the Ouachita and Ozark Mountains of Arkansas and Oklahoma to quantify the impacts of oak decline on forest structure. Plots were identified as either high risk (red oak basal area ≥ 20 square feet per acre) or low risk (red oak basal area < 20 square feet per acre). Red oak had the highest importance values on high-risk plots whereas shortleaf pine was the most important species on low-risk plots. Fifty percent of red oak density and 53 percent of red oak basal area were dead or dying on high-risk plots. In contrast, 20 percent of red oak density and 20 percent of red oak basal area were dead or dying on low-risk plots. Red oaks on all plots were killed regardless of tree d.b.h. Sapling and seedling regeneration on high-risk plots was dominated by nonoak, shade-tolerant species. In severely impacted areas, oak decline appeared to be accelerating a change in long-term species composition away from oak-dominated forests.

INTRODUCTION

Since 1999, widespread and locally severe mortality of red oaks has been observed in the Ozark Mountains of Arkansas and Missouri and the Ouachita Mountains of Arkansas and eastern Oklahoma. Mortality has been attributed to oak decline, a disease complex caused by predisposing, inciting, and contributing factors that interact and result in mortality, particularly for red oaks (Starkey and others 1989). Oak decline is a natural and recurring phenomenon in the Southern United States. However, the level of mortality associated with the current decline is unprecedented in the Ozark and Ouachita Mountains. At least 300,000 acres in Arkansas and more than 100,000 acres in Missouri have been severely damaged (Lawrence and others 2002, Spencer 2001).

In the current episode, Mielke (2001) and Starkey and others (2000) have suggested the predisposing factors include high proportions of red oak in stands, advanced tree age, and shallow, rocky soils. The inciting factor was probably a pronounced regional drought from 1998 to 2000. Contributing factors are the red oak borer [*Enaphalodes rufulus* (Haldeman) (Coleoptera: Cerambycidae)] and, more speculatively, other organisms such as *Armillaria* spp. root rot, *Hypoxylon* spp. stem canker, and two-lined chestnut borer [*Agrilus bilineatus* (Weber)]. The role of red oak borer in this decline is particularly remarkable. The insect is native to the Eastern and Southern United States. It feeds in the phloem and xylem of living oak trees, with preferred upland hosts being northern red oak (*Quercus rubra* L.), black oak (*Q. velutina* Lam.), and scarlet oak (*Q. coccinea* Muenchh.) (Donley and Acciavatti 1980, Solomon 1995). Species in the white oak group [including white oak (*Q. alba* L.) and post oak (*Q. stellata* Wangenh.)] are less commonly attacked. Normally, red oak borer populations are too low to kill trees. However, recent dissections of dead and declining trees in Arkansas indicated that borer populations were at unprecedentedly high levels (Stephen and others 2002).

Despite the magnitude of the disturbance, no formal studies have examined the impacts of oak decline on the forest structure of the region. In 2002, field plots were established in Arkansas and Oklahoma to quantify the distribution and severity of oak decline. This fieldwork initiated a larger project that will include additional plots in Arkansas, Oklahoma, and Missouri. For this paper, we used preliminary field plot data to describe (1) the structural characteristics of stands having high and low mortality levels, and (2) the regeneration status of high-mortality stands.

METHODS

In July and August 2002, 44 field plots were established throughout the Ozark Mountains of northern Arkansas and the Ouachita Mountains of western Arkansas and eastern Oklahoma. Most plots were located on the Ozark-Saint Francis National Forest and the Ouachita National Forest. Elevations ranged from 490 to 2,200 feet. Plots were located on a variety of topographic positions and aspects. Site index was generally 50 to 60 feet for upland oak at base age 50 years. Most slopes were 10 to 40 percent, although slopes exceeding 55 percent were recorded.

The field methods for site selection have been developed for similar forest health issues of oak, specifically, gypsy moth, ozone, and, most recently, sudden oak death syndrome (Smith 1995). The basic approach is to generate 500 units of area, called polygons, where each polygon is stratified by the proportion of stands it contains at high or low risk using available Forest Service data within each polygon. In this study, the sample design had a large expansion factor; the inventory was designed to sample approximately 500 plots, or roughly 1 plot for every 50,000 acres of forest land in the Ozark and Ouachita Mountains. An expert systems approach was used to identify variables of importance in quantifying risk strata for oak decline, based on red oak basal area, aspect, and site index. The sample was then stratified in such a manner as to visit more polygons in the higher risk categories and fewer in

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

the lower risk categories. But, because a 50,000-acre polygon contains a variety of stands, often the stand actually visited did not match the classifying parameters. Thus, final stratification of plots was based on data actually collected in the field rather than through *a priori* assignment.

Plots consisted of one 0.2-acre overstory plot in which all living, dying, and dead trees ≥ 9.6 inches in d.b.h. were tallied by species, tree condition, and d.b.h. Tree condition was recorded as: alive and healthy, alive but dying, or dead within the past 3 years. Trees that died more than 3 years ago were not recorded. A series of smaller plots were nested within each 0.2-acre plot. These included: one 0.1-acre midstory plot in which all living, dying, and dead trees 3.6 to 9.5 inches in d.b.h. were tallied by species, tree condition, and d.b.h,; two 0.01-acre sapling plots in which we recorded living trees 1.6 to 3.5 inches in d.b.h. by species and d.b.h.; and eight 0.001-acre regeneration plots in which tree seedlings less than 1.6 inches in d.b.h. and taller than 1.5 feet were tallied by species and 1-foot height class.

Plots were established in stands having varying proportions of red oak. Some plots were dominated by red oak, whereas others contained no red oak at all. Because red oak is more susceptible than white oak to oak decline, we assumed that plots with a high proportion of red oak were at greater risk than plots with relatively few red oak. Therefore, we defined high-risk plots as having at least 20 square feet per acre of red oak basal area (including living and dead or dying trees) and low-risk plots as having less than 20 square feet per acre of red oak basal area. Of the 44 plots established, 18 were classified as high risk and 26 as low risk.

For trees ≥ 3.6 inches in d.b.h. on high- and low-risk plots, importance values (IV) for each species or species group were calculated using the equation IV=(relative density + relative basal area)/2. For all 44 plots, we used simple linear regression to explore the relationship between the total (i.e., living plus dead or dying) red oak basal area in a given plot and the dead or dying red oak basal area in the same plot. Significance was accepted at $P \leq 0.05$.

RESULTS AND DISCUSSION

Species importance values differed between high-risk and low-risk plots (table 1). Red oak had the highest species importance values on the high-risk plots, whereas shortleaf pine (*Pinus echinata* L.) was the most important species on the low-risk plots. On the high-risk plots, the order of species importance was red oak > other species > white oak > shortleaf pine. On the low-risk plots, the order of species importance was shortleaf pine > other species > white oak > red oak. Other species on high- and low-risk plots included hickory (*Carya* spp.), red maple (*Acer rubrum* L.), blackgum (*Nyssa sylvatica* Marsh.), and numerous associated species (table 1).

Red oak mortality was dramatic on the high-risk plots (table 2). For trees ≥ 3.6 inches in d.b.h., 53 percent of red oak density and 50 percent of red oak basal area were dead or dying. In contrast, 13 percent of white oak density and 7 percent of white oak basal area were dead or dying. Shortleaf pine and other species appeared to be relatively healthy. Including all species, 57 trees per acre and 25 square feet per acre were dead or dying on the high-risk plots. Red oak mortality was less pronounced on the low-risk plots (table 3). For trees ≥ 3.6 inches in d.b.h., 20 percent of red oak density and 20 percent of red oak basal area were dead or dying. Interestingly, white oak mortality as expressed in density (11 percent) and basal area (16 percent) was similar to or exceeded the white oak mortality recorded on high-risk plots. Shortleaf pine and other species on the low-risk plots were generally in good condition. Overall, only 16 trees per acre and 6 square feet per acre were dead or dying on the low-risk plots.

Table 1—Species importance values for trees ≥ 3.6 inches d.b.h. on high risk plots (red oak basal area ≥ 20 square feet per acre) and low risk plots (red oak basal area < 20 square feet per acre) in Arkansas and Oklahoma

Species	Importance values	
	High risk plots	Low risk plots
	percent	
Red oak[a]	35	7
White oak[b]	24	22
Shortleaf pine	11	37
Other species[c]	30	34

[a] Includes northern red oak, southern red oak, black oak, and blackjack oak (*Quercus marilandica* Muenchh.).
[b] Includes white oak and post oak.
[c] Includes hickory, red maple, blackgum, flowering dogwood (*Cornus florida* L.), winged elm (*Ulmus alata* Michx.), black cherry (*Prunus serotina* Ehrh.), white ash (*Fraxinus americana* L.), eastern hophornbeam (*Ostrya virginiana* (Mill.) K.Koch), eastern redcedar (*Juniperus virginiana* L.), sweetgum (*Liquidambar styraciflua* L.), black walnut (*Juglans nigra* L.), sugar maple (*Acer saccharum* Marsh.), American beech (*Fagus grandifolia* Ehrh.), and sassafras [*Sassafras albidum* (Nutt.) Nees].

Including data from all 44 plots, there was a statistically significant linear relationship ($P \leq 0.05$) between the total red oak basal area in a given plot and the dead or dying red oak basal area in the same plot (fig. 1). Not surprisingly, the highest basal area of dead or dying red oak was generally found in plots dominated by red oak. However, red oak-dominated plots differed in the extent to which they had been affected by oak decline. For example, almost all of the red oak basal area on plots 12 and 16 was dead or dying. On plots 34 and 40, however, a relatively low proportion of red oak basal area was dead or dying, even though total red oak basal area was 45 and 60 square feet per acre, respectively. This suggests that other factors such as topographic position, aspect, tree age, and proximity to red oak borer populations may also influence tree susceptibility to decline (Oak and others 1996, Starkey and Oak 1989).

Table 2—Stand characteristics for healthy and dead or dying trees ≥ 3.6 inches d.b.h. on high risk plots (red oak basal area ≥ 20 square feet per acre) in Arkansas and Oklahoma

Species	Density		Basal area	
	Healthy	Dead/dying	Healthy	Dead/dying
	trees per acre		*square feet per acre*	
Red oak[a]	38	42	21	21
White oak[b]	47	7	26	2
Shortleaf pine	22	1	15	< 1
Other species[c]	83	7	25	2
Total	190	57	87	25

[a] Includes northern red oak, southern red oak, black oak, and blackjack oak.

[b] Includes white oak and post oak.

[c] Includes hickory, red maple, blackgum, flowering dogwood, winged elm, black cherry, white ash,eastern hophornbeam, eastern redcedar, sweetgum, black walnut, sugar maple, American beech, and sassafras.

Table 3—Stand characteristics for healthy and dead or dying trees ≥ 3.6 inches d.b.h. on low risk plots (red oak basal area < 20 square feet per acre) in Arkansas and Oklahoma

Species	Density		Basal area	
	Healthy	Dead/dying	Healthy	Dead/dying
	trees per acre		*square feet per acre*	
Red oak[a]	12	3	5	1
White oak[b]	39	5	16	3
Shortleaf pine	59	7	35	2
Other species[c]	78	1	26	< 1
Total	188	16	82	6

[a] Includes northern red oak, southern red oak, black oak, and blackjack oak.

[b] Includes white oak and post oak.

[c] Includes hickory, red maple, blackgum, flowering dogwood, winged elm, black cherry, white ash,eastern hophornbeam, eastern redcedar, sweetgum, black walnut, sugar maple, American beech, and sassafras.

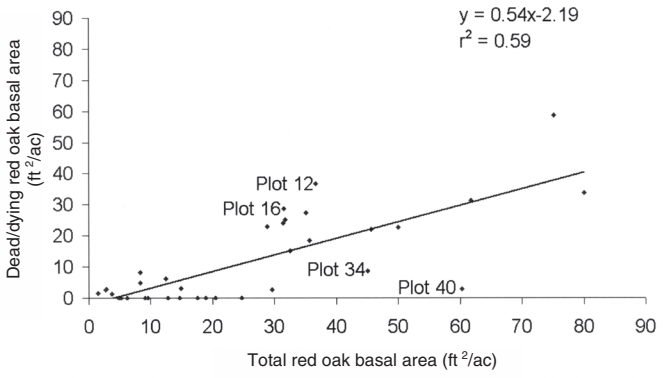

Figure 1—Relationship between total red oak basal area and dead or dying red oak basal area for trees ≥ 3.6 inches d.b.h. on high risk plots (red oak basal area ≥ 20 square feet per acre) and low risk plots (red oak basal area < 20 square feet per acre) in Arkansas and Oklahoma.

The diameter distribution of dead/dying red oak from all 44 plots was different from the diameter distribution of all dead or dying white oak (figs. 2a and 2b). Red oak mortality was observed across a range of diameters; high proportions of small, mid-sized, and large d.b.h. red oak trees were dead or dying (fig. 2a). In contrast, white oak mortality was greatest in small diameter trees (particularly the 4-inch d.b.h. class) and decreased with increasing diameter (fig. 2b). Such a pattern may indicate that red oak borers – which prefer red oak over white oak - can effectively kill trees of any size, whereas the factors responsible for the death of white oak generally kill small and presumably suppressed stems. Small-diameter white oaks are not necessarily young trees; although considered intermediate in shade tolerance, white oaks can persist in shaded understory conditions for decades (Rogers 1990).

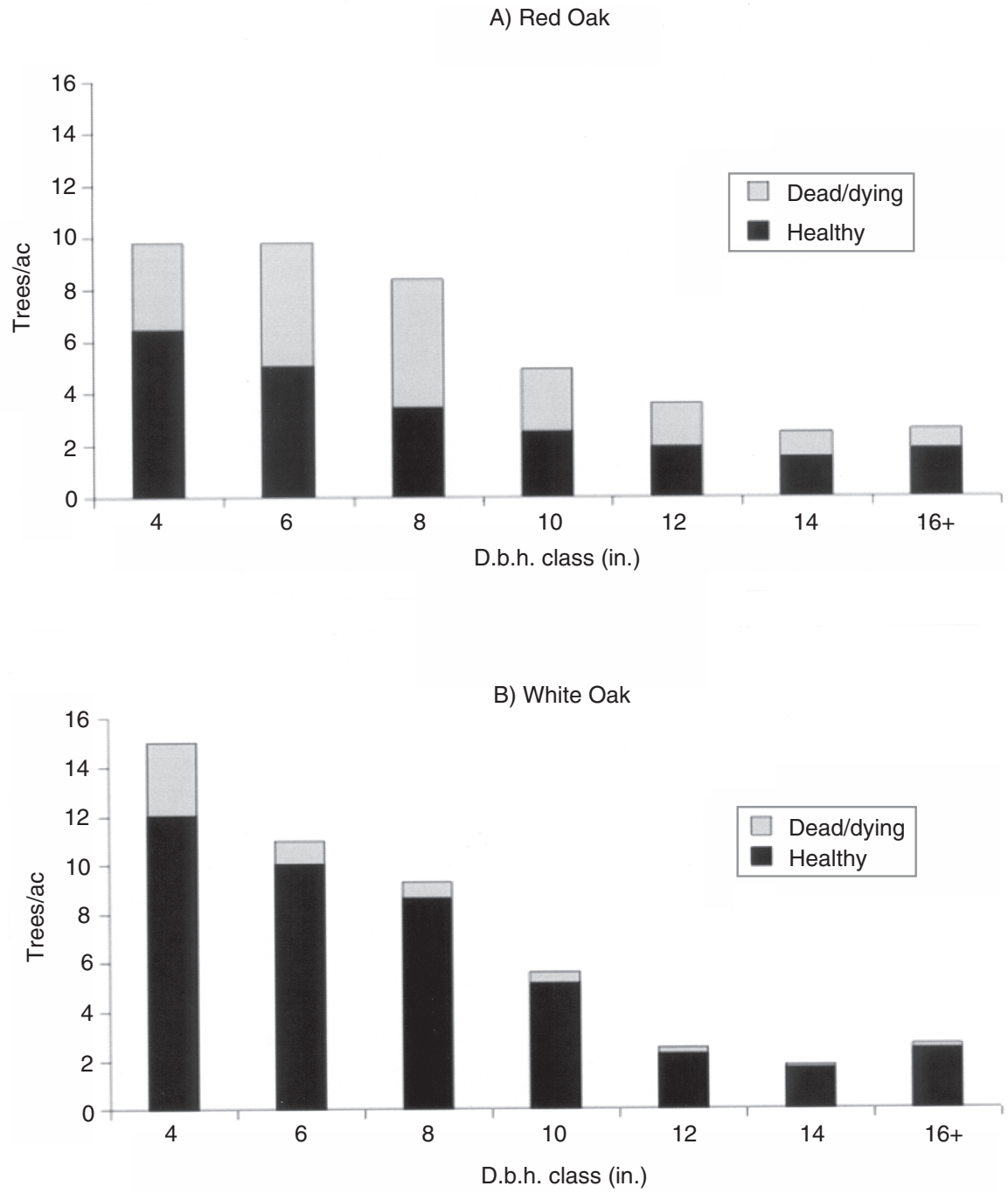

Figure 2—Diameter distribution of healthy and dead or dying (A) red oak and (B) white oak ≥ 3.6 inches d.b.h. on high risk plots (red oak basal area ≥ 20 square feet per acre) and low risk plots (red oak basal area < 20 square feet per acre) in Arkansas and Oklahoma.

On many of the high-risk plots, field observations indicated that oak mortality had triggered a regeneration response. On the high-risk plots, data indicate that the vast majority of sapling and seedlings in all d.b.h. and height classes were nonoak species (table 4). Indeed, only 16 percent of saplings and 18 percent of seedlings were oaks. Regenerating stems were predominantly shade-tolerant red maple, blackgum, and flowering dogwood (*Cornus florida* L.). Most red and white oak seedlings were in the 2- and 3-foot height classes. Previous research in the Missouri Ozarks suggested that such short oak seedlings have a low probability of survival (Sander 1972, Sander and others 1984).

Many mature oak forests in the Southern and Eastern United States are characterized by understories of shade tolerant, nonoak species (e.g., Abrams 1998, Lorimer and others 1994). In severely impacted forests in the Ozark and Ouachita Mountains of Arkansas and Oklahoma, it seems likely that oak decline is accelerating a long-term change in species composition toward fewer oaks. Data will

Table 4—Density of saplings (1.6–3.5 inches d.b.h.) and seedlings (< 1.6 inches d.b.h. and >1.5 feet tall) on high risk plots (red oak basal area ≥ 20 square feet per acre) in Arkansas and Oklahoma

	D.b.h. class (*inches*)			Height class (*feet*)			
Species	1	2	3	2	3	4	≥ 5
	Saplings per acre			*Seedlings per acre*			
Red oak[a]	3	13	8	181	28	28	0
White oak[b]	0	6	6	42	14	7	0
Other species[c]	49	81	60	729	306	146	167
Total	52	100	74	952	348	181	167

[a] Includes northern red oak, southern red oak, black oak, and blackjack oak.
[b] Includes white oak and post oak.
[c] Includes hickory, red maple, blackgum, flowering dogwood, winged elm, black cherry, white ash, eastern hophornbeam, eastern redcedar, sweetgum, American beech, sassafras, shortleaf pine, black locust (*Robinia pseudoacadia* L.), hawthorn (*Crataegus* spp.), downy serviceberry (*Amelanchier arborea* (Michx.f.) Fern.), and American hornbeam (*Carpinus caroliniana* Walt.).

be collected in 2003 from many additional field plots in Arkansas, Oklahoma, and Missouri to more completely describe the changes in forest structure occurring throughout the region.

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NANTUCKET PINE TIP MOTH CONTROL AND LOBLOLLY PINE GROWTH IN INTENSIVE PINE CULTURE: TWO-YEAR RESULTS

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Abstract—Twenty-two treatments replicated four times were applied to planted loblolly pine, *Pinus taeda* L. on bedded industrial forest land in east Texas for measurement of growth impact of Nantucket pine tip moth (NPTM), *Rhyacionia frustrana (*Comstock), and effects on pine growth over 2 years. Treatments were combinations of Velpar, Oust, and Arsenal herbicides and diammonium phosphate (DAP) fertilizer with treatments in 2000, or both 2000 and 2001. Ten of the treatments were treated with Mimic timed with pheromone traps to reduce NPTM infestations. Mimic was an effective control, and there was a small but significant increase in the loblolly pine growth at the end of the second growing season. The best growth of pines with the most intensive treatments was equal with and without NPTM control. NPTM control did, however, make a difference on intermediate treatments.

INTRODUCTION

The Nantucket pine tip moth, *Rhyacionia frustrana* (Comstock) (NPTM), is an important pine regeneration insect in the Eastern and Southern United States (Berisford 1987). Larval feeding in meristematic tissue of young pines causes significant damage, particularly in areas where forest regeneration favors its proliferation (Yates and others 1981). Southeastern industrial forestry currently emphasizes establishment of large, homogeneous pine plantations to maximize production of wood and fiber. This forest management practice also creates optimal conditions for phytophagous insects, whose sole or primary hosts are pine trees. Increased damage by NPTM following vegetation control treatments may include improved suitability of pine tissue for larvae and a greater abundance of NPTM feeding sites (Ross and Berisford 1990). NPTM infestation rates tended to increase as site preparation intensity increased and levels of competing vegetation and overstory decreased (Berisford and Kulman 1967, Hertel and Benjamin 1977, Hood and others 1988, Lantagne and Burger 1988, White and others 1984, Zutter and others 1986). Miller and Stephen (1983) indicated competing herbaceous and woody vegetation provides food and shelter for NPTM predators and parasites.

Pritchert and Smith (1972) observed little change in NPTM infestation on trees fertilized with nitrogen. Application of phosphorus, however, resulted in a significant NPTM reduction, with potassium reducing NPTM even further. Tiarks and Haywood (1986), in a study measuring effects of fertilization and vegetation control on loblolly pine, observed uniform NPTM damage across all treatments, but NPTM infestation rates were not quantified. Meeker (1987) found a negative correlation between NPTM levels in soil and foliage, and NPTM infestation rates, with increasing levels of phosphorus associated with decreasing infestation rates. Reasons for this are not known, but increased vigor may serve to bolster the trees' natural defenses, particularly resin production (Berisford 1987).

Herbicides, including Sulfometuron methyl (Oust®) and Hexazinone (Velpar®-L), are commonly used to reduce competing herbaceous vegetation in loblolly pine plantations (Cantrell and others 1985, Creighton and others 1986, Michael 1985, Yeiser and Boyd 1989, Yeiser and Rhodenbaugh 1994). Use of herbicides for vegetation management continues to increase (Dubois and others 1999) along with growth (Glover and others 1994); fertilization at planting has been applied to 200,000 acres of southern pines. The resulting population of NPTM following herbicide applications and fertilizers, especially addition of phosphorus, warrants additional investigation. Ross and others (1990) found that the percentage of infested trees and the percentage of infested shoot tips were significantly higher in the banded and broadcast-treated plots than in check plots during the third NPTM generation.

METHODS

Twenty-two six-tree by six-tree plots with a two-row buffer were established on an Upper Coastal Plain industrial forest site with a fine sandy silt loam near Diboll, Angelina County, TX, in early 2000. The study was a complete randomized block with 22 treatments (table 1) replicated four times. The area was site prepared with pre-emergent herbicides and combination plowed with loblolly pine planted on the beds.

Mimic® 2LV Insecticide (active ingredient, tebufenozide) was applied following label instructions on a per-acre basis five times each season timed with pheromone traps baited with synthetic NPTM lures. Mimic registration changed from Rohm and Haas, and ownership of the product to Dow AgroSciences LLC, June 1, 2001. Dr. Don Grosman, Forest Pest Management, Texas Forest Service, Lufkin, provided NPTM trap catch data and advice on Mimic timing for application. NPTM infestations were counted on a whole-tree basis after the third generation in 2000, at the end of the season (fifth generation overwintering in the tips), after the third generation in 2002, and at the end of the season (fifth generation). Infestations were counted on

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Table 1—Herbicide and fertilizer treatments, 2000–2001

March Herbicide/ Fertilizer[a]	June Herbicide[b]	March Herbicide/ Fertilizer[a]
- - - - - - - - - - - - 2000 - - - - - - - - - - - -		2001
VO[c]		
VO/125 DAP[c]		
VO/250 DAP[c]		
VO/125 DAP[c]	AO	
VO[c]	AO	
VO[c]		AO
VO/125 DAP[c]		AO/125 DAP
VO/250 DAP[c]		AO
VO/	AO	AO
VO/125 DAP[c]	AO	AO/125 DAP
VO/250 DAP[c] AO[c]	AO	AO
CHECK		

[a] VO = Velpar (10.7 ounces) + Oust (2 ounces.); AO = Arsenal (4 ounces.) + Oust (2 ounces.)

[b] DAP = diammonium phosphate.

[c] Mimic = Treatments replicated with and without Mimic; five applications of 8 ounces of product per acre Mimic each season, 2000 and 2001 timed to the 1st instar larvae of the Nantucket Pine Tip Moth with pheromone traps.

the (1) terminal (infested or not infested); (2) top whorl except for the top terminal; (3) top 1/2 of the tree; and (4) bottom 1/2 of the tree. Each tip was examined as infested or uninfested. A total tree count was taken for the site for each of the treatments over the replications. Data were analyzed with SAS, with an ANOVA using New Duncan's Multiple Range Test at the p=0.05 (SAS 1988).

RESULTS AND DISCUSSION

Data were analyzed for NPTM infestation at the end of the second growing season (2002). In additional to NPTM, coneworms, *Dioryctria* spp. infested nodes of the main stem causing either breakage of lateral branches or the main stem in limited instances. There was no difference in survival for either year 1 or year 2 for the Mimic and non-Mimic treatments, with 88.1-percent survival with Mimic in year 1 and 87.9-percent survival without Mimic; and 86.3-percent survival for both Mimic and no Mimic treatments in year 2.

Height was significantly greater for Mimic treatments in year 1 and year 2. In year 1, Mimic treatments averaged 2.2 feet, non-Mimic 2.1 feet. In year 2, Mimic treatments averaged 7.2 feet, non-Mimic 6.6 feet. For cubic foot volume, Mimic-treated plots were greater in year 1, 0.0102 cubic feet volume index compared to 0.0095 for non-Mimic treatments. In year 2, Mimic-treated plots averaged 0.26 cubic feet and non-Mimic plots 0.21 cubic feet. Ground-line diameter (inches) was significantly greater in Mimic treatments, 0.72 inches Mimic, 0.69 inches non-Mimic in year 1 and 2.13 inches Mimic, 1.98 inches non-Mimic in year 2.

A more detailed analysis of volume index (cubic feet) for year 2 indicated significant differences in whole tree NPTM infestations (table 2). There were no differences in NPTM infestation for all Mimic treatments, with a mean of 0.6 infested tips for the whole tree. Without Mimic treatments, there was an average of 8.0 infested tips per tree.

For non-Mimic treatments, NPTM infestations were significantly higher on the check plots (10.46 infested tips); VO (Velpar/ Oust) + 125 pounds DAP (diamonnium phosphate fertilizer), VO + AO (Arsenal/ Oust) + 125 pounds DAP (2000), and VO + AO (2000) and AO (2001) had the highest infestations among the treatments whereas VO + 250

Table 2—Whole tree infestations, NPTM, 2002, for fertilizer, herbicide, Mimic and check treatments

Treatments				Volume index (cubic feet)[a]		NPTM whole tree infestation	
- - - - 2000 - - - -		- - - 2001 - - -		- - - - - - - - - - - - - - - Mimic - - - - - - - - - - - - - - -			
Herb.	Fert.	Herb.	Fert.	No	Yes	No	Yes
VO				0.1325f	0.1730d	7.47dc	0.30f
VO	125			0.1758e	0.1923cd	9.70a	0.46f
VO	250			0.1987de	0.2128c	7.50dc	0.54f
VO/AO	125			0.2249d	0.2280c	9.50ba	0.45f
VO/AO	250			0.1835e	0.2090cd	8.42cb	0.40f
VO		AO		0.2070de	0.2774b	5.65e	0.60f
VO	125	AO	125	0.2871bc	0.3263a	7.07d	0.63f
VO	250	AO		0.2649c	0.3481a	5.19e	0.71f
VO/AO		AO		0.2215d		9.32ba	
VO/AO	125	AO	125	0.3114ab	0.3304a	8.14dc	1.00f
VO/AO	250	AO		0.3234a	0.3307a	7.35dc	0.68f
CHECK				0.0834g		10.46a	
			Mean	0.2174b	0.2615a	8.00	0.60

NPTM = Nantucket Pine Tip Moth.

[a] Means significantly different, $p < 0.05$; means followed by the same letter are not significantly different, Duncan's New Multiple Range Test.

pounds DAP (2000) and AO (2001), and VO (2000) and AO (2001) had the lowest. Intermediate infestations ranged from 7.07 to 8.42 infested tips.

The least volume growth occurred on the check plots (0.0834 cubic feet). The greatest volume growth occurred on six treatments, four with Mimic and two without Mimic, with the highest being VO + 250 pounds DAP (2000) and AO (2001) + Mimic. Those treatments without Mimic that had significantly greater volume were VO + 250 pounds DAP (2000) and AO (2001), and VO + 125 pounds DAP (2000) and AO + 125 pounds DAP (2001) (table 2).

NPTM infestations ranged from 7.35 to 8.14 infested tips for the intensive treatments that did not differ in cubic foot volume with or without Mimic (table 2). For intensive treatments where Mimic applications were significant, NPTM infestations were lowest on the VO + 250 lbs. DAP (2000) and VO (2001) treatments.

During a year of low to moderate NPTM infestations (2001), the most intensive cultural treatments had similar volume growth with or without Mimic for NPTM control (table 2). Mimic applications were significant with intermediate treatments (VO + 125 pounds DAP (2000) and AO + 125 pounds DAP (2001); and VO + 250 pounds DAP (2000) and AO (2001).

SUMMARY

For 2001, a year of low to moderate NPTM infestations, the most intensive cultural treatments showed no difference in cubic feet volume growth with or without Mimic. For intermediate cultural treatments, Mimic applications yielded a significant increase in tree volume. The timing of spraying coupled with the cost of the insecticide and the labor for application need to be considered in long-term intensive management of industrial pine plantations. Timing and frequency of Mimic applications need to be examined in years of high NPTM infestations.

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EFFECTS OF *BOTRYOSPHAERIA* INOCULATION AND STRESS DURING LIFTING AND OUTPLANTING ON INITIAL GROWTH OF OUTPLANTED SWEETGUM SEEDLINGS

William Carey, Dave Gerwig, Bert Cregg, and Scott Enebak[1]

Abstract—A coordinated investigation was carried out with sweetgum seedlings from a nursery in South Carolina (SC) and one in Virginia (VA) to evaluate the effects of cultural practices and *Botryosphaeria* on the establishment and initial growth of transplanted sweetgum. Seedlings from VA were more sensitive to treatments than those from SC, and date of leaf emergence after planting correlated with subsequent growth ($r = 0.79$, $p = 0.01$). Inoculation with *Botryosphaeria* had little impact on seedlings, but increased care during lifting and reduced seedling exposure at lifting and at the planting site increased early growth and survival of seedlings.

INTRODUCTION

The impetus for investigating the impact of *Botryosphaeria* on sweetgum was widespread dieback among seedlings planted near Summerville, SC, in the winter of 1995-96. These seedlings, lifted in late January and planted in mid-February, were exposed to several freezes alternating with warmer temperatures. By mid-May, seedlings were flushing late with undersized leaves. There was extensive dieback at all visited sites, and many seedlings that were resprouting near the root collar had sunken, black cankers characteristic of *B. dothidea* (syn *B. ribis*) (Filer and Randall 1978) on the stems above the new growth. Whether these cankers originated before or after lifting is not known, and the natural phenology of infection and symptom expression for *Botryosphaeria,* or its impact, on transplanted sweetgum is not known. The disease is considered unimportant on established sweetgums (Toole 1957) where it colonizes only weakened branches. However, the stresses associated with lifting, storage, and outplanting can allow even weak pathogens to reduce survival and growth. At a site visited in 1996, 96 percent of the seedlings planted by research personnel had produced foliage compared to 49 percent of seedlings planted operationally. This seemed to imply that there is an effect of planting care in the rate of foliage production. Because similar problems were also affecting plantation establishment at Union Camp Corporation, a coordinated investigation was carried out to assess cultural practices and the effects of *Botryosphaeria* on the establishment and initial growth of transplanted sweetgum.

METHODOLOGY

Field trials were arranged between the Nursery Cooperative, Westvaco (now MeadWestvaco) and Union Camp (now International Paper) Corporations in the spring of 1997 to evaluate the effects of cultural practices associated with transplantation on growth, mortality, and disease development. Westvaco's nursery (SC seedlings) and planting site are near Summerville, SC, and Union Camp's nursery (VA seedlings) is near Capron, VA. The planting site (the Trice Research Forest or TRF) is near Sumter, SC. Seedlings from both nurseries were inoculated with *Botryosphaeria* to evaluate the effect on transplant stress. Seedlings were exchanged between corporations to assess differences for nursery source.

Three treatments specifically evaluating the effect of *Botryosphaeria* were made on January 15, 1997. These were (1) wound-inoculation, (2) wounding without inoculation, and (3) a fungicide treatment (a stem spray at Summerville and a root dip at TRF with 2.4 g a.i. per L Captan [reported by Pusey and Okie (1996) to reduce infections on peach]. Wounds were made 6 inches above the root collar with a sterile 3-mm-diameter cork borer, and the "bark" was removed and replaced with a disc of *B. dothidia* growing on PDA (Difco®) or with sterile PDA. These wounds were wrapped with Parafilm® to retard dessication.

At Summerville, seedlings lifted in January were separated into 140 10-seedling replicates. Four exposure treatments were created by exposing half the replicates for 20 minutes before storage and later exposing half of those already exposed and half of those not exposed (35 each) for 20 minutes just before planting. Of the 35 reps to receive each exposure treatment, 10 received no additional treatment, 10 were inoculated with *Botryosphaeria,* 5 were wounded but not inoculated, and 10 were sprayed with Captan. Two levels of exposure at the planting site, for each of 10 10-seedling-replicates from VA brought the total number of treatments to 14. One rep of seedlings from each treatment was planted together in a block. Half of the 10 replicates receiving each treatment were planted in 5 blocks with and 5 blocks without subsequent weed control. A 15th treatment of wounded but not inoculated seedlings was planted only in weed controlled plots. Leaf expansion was recorded on a four-point scale where 1 = closed bud, 2 = bud break, 3 = early expansion, and 4 = full expansion.

At the TRF, 11 treatments were applied to both operationally and to carefully lifted VA seedlings from a single family. In addition, 2 levels of preplant exposure were given SC seedlings for a total of 24 treatments. Seedlings were lifted on January 30 and remained in cold storage (less treatment requirements) until planted on February 13. Height

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

and diameter were measured immediately after planting. Data are presented by treatment only for those treatments applied by the Nursery Coop (*Botryosphaeria* inoculation and fungicide treatment), but the other treatments are listed in appendix table 1. Coop treatments were: (1) no postlift treatment, (2) inoculation, (3) inoculation plus a Captan, or (4) wounding without inoculation. The production of leaves was assessed on March 10, 24, and on April 1 using a three-point scale, where 0 = closed bud, 1 = swollen buds, and 2 = expanding leaves. Seedling heights, diameters, and survival were assessed again in September.

Analyses

All seedlings were analyzed for the effects of exposure, inoculation, fungicide, block, and herbicide (nested in block) at Summerville. TRF treatments coordinated with the Nursery Coop were analyzed for the effects of lifting, treatment, and block. Nursery source was analyzed for each planting site, with the exchanged seedlings compared only to similar treatments from the host nursery. Comparisons between means were made using Duncan's at $\alpha = 0.05$. At TRF, the correlation between April leaf emergence and September stem heights was assessed for all 24 treatments.

RESULTS AND DISCUSSION

Nursery source is compared for similar treatments at each planting site in table 1. SC seedlings flushed sooner and died back less at both sites. More SC seedlings had live stem above the ground at both sites, but the difference was not significant at TRF (P = 0.21). At Summerville, seedlings from both nurseries were planted with 0 or 20 minutes exposure at the planting site. Although only the main effects for nursery source and for planting site are presented, there was a significant interaction (not presented) for source at Summerville because VA but not SC seedlings responded to exposure with increased dieback.

The effects of inoculation and fungicide spray on SC seedlings planted at Summerville are presented in table 2. Seedlings from VA but not those from SC were sensitive to exposure at the planting site. A small difference in initial dieback (4 percent vs 2 percent) for the fungicide spray was an exception to the lack of treatment effects among SC seedlings. Weed control significantly affected seedling growth but is not covered in this report. No inoculations at Summerville produced cankers, and most inoculation wounds healed entirely.

Table 1—Comparisons for nursery source for similarly treated sweetgum seedlings planted at two sites in SC

Planting site	Origin	Survival	Leaf development[a]	Dieback[b]
			percent	
Summerville	SC	98a	3.5a	2a
	VA	63b	1.3b	44b
	lsd	8	0.3	9
TRF	SC	96	1.8a	4.5a
	VA	89	1.5b	25.2b
	Lsd	11	0.2	14.4

TRF = Trice Research Forest.
[a] Leaf development is a three point scale at TRF on April 4 and a four point scale at Summerville on April 3.
[b] Dieback at TRF is quantitative per plant as percentage of initial height, whereas at Summerville it is qualitative per plant as the percentage of trees with dieback.

The effects of wounding, wounding plus inoculation, and wounding, inoculation, and fungicide root dip among VA seedlings planted near Sumter, SC, are presented in table 3. In contrast to the results at Summerville for SC seedlings, the VA seedlings responded to additional treatments with reduced growth and more dieback. Among the four treatments comparing the effects of inoculation and a potential fungicide control, care in lifting resulted in significant effects without interaction.

Together, all treatments at the TRF (eight at two levels of lift in addition to those in table 3) indicated the sensitivity of those sweetgums to cultural treatments that could be associated with transplanting. There was a strong correlation between time of leaf emergence, which can easily be evaluated early in the season, and subsequent dieback, survival, and growth. Figure 1 presents the relationship

Table 2—Effects of *Botryosphaeria* inoculation or Captan spray[a] on sweetgum seedlings lifted at Summerville, SC, and planted nearby in 1997

Treatment[b]	n	Leaf development[c]	Dieback	Survival	Growth
			- - - - - - - - - *percent* - - - - - - - - -		
Spray = Captan	40	3.49	4.0a	98.2	197
Spray = None	80	3.47	1.9b	98.6	193
lsd		0.96	1.9	1.3	7
I = Botryosphaeria	40	3.48	1.7	98.2	193
I = None	80	3.47	3.0	98.6	195
lsd		0.96	1.9	1.3	7

Dieback = the percentage of seedlings with any (qualitative) terminal necrosis in April;
Survival = the percentage of seedlings with any live stem above ground in November;
Growth percent = the average percentage increase in height from April to November.
[a] Averaged over four post-lifting exposure treatments.
[b] Captan, 2.5 percent a.i. sprayed to wet stem, *Botryosphaeria* on PDA placed in a wound then sealed with wax-tape.
[c] Leaf development was assessed (April 3) on a four point scale.

Table 3—Effects of inoculation and lifting treatments on survival and early growth of sweetgum seedlings from VA, planted near Sumter, SC[a] in 1997

Treatment[b]	n	Leaf development[c]	Dieback	Survival
		- - - - - - - - - *percent* - - - - - - - - -		
I = Control	10	1.68	25a	89a
I = Wound only	10	1.67	26a	85a
I = Botryosphaeria	10	1.53	33ab	79ab
I = Botryosphaeria + root dip	10	1.51	43b	70b
lsd		0.20	0.11	12
Lift = Research	20	1.60	25a	89a
Lift = Regular	20	1.59	38b	72b
lsd		0.14	8	8.7

Dieback = the average length of dead terminal (feet) in April 1997; Survival = the percentage of seedlings with any live stem above ground in April.

[a] Trice Research Forest.

[b] "I" is inoculation at two levels of lifting. The Captan is a root dip with 2.5 percent a.i. solution on inoculated seedlings, inoculation is *Botryosphaeria* on PDA in a wound then sealed with wax-tape.

[c] Leaf development was assessed (April 4) on a three point scale (0, 1 or 2) where 2 = expanding. The means for Leaf development and Dieback do not include dead seedlings.

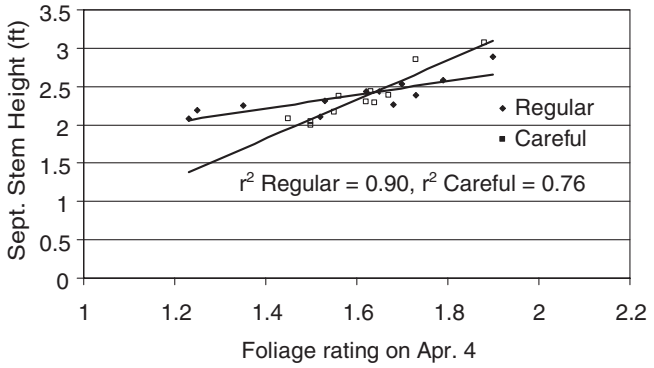

Figure 1—The correlation between bud break (measured in April) and sweetgum height (in feet) measured in September for all treatments planted at the Trice Research Forest.

between spring flush and height at the end of the growing season.

Although it should be remembered that seedlings from the two nursery sources were not handled exactly the same, inference from the two study sites is contradictory in that sweetgum was (VA source) or was not sensitive to treatments associated with lifting, storage, and planting. Artificial inoculation with *Botryosphaeria* had little impact on seedlings from either source. This appears to confirm that the fungus is a very weak pathogen of sweetgum (Toole 1957). Among seedlings presented for inoculation in 1997, no SC seedlings and 4.5 percent of VA seedlings already had stem cankers. The stress that predisposed some VA seedlings to cankering probably predisposed them and others to the treatments in the present study. The cankers observed on SC seedlings the preceeding spring (1996) probably indicate earlier conditions that predisposed those seedlings to respond to differences in planting technique with dramatic differences in dieback (as described in the introduction) unlike same-source seedlings in the present study.

Management Implications

This research indicated, as did differences in foliage production between seedlings planted by research and contract planters near Summerville in 1996, that sweetgum can be sensitive to cultural practices that could be part of harvest, storage, and transplanting. Further, this sensitivity may vary between crops or between nurseries, probably due to conditions at the nursery before lifting. Therefore, provisions to limit exposure or rough handling, or both, during harvest and planting may enhance early growth and survival of seedlings more for some years' crops than for others. However, such care is always a good practice.

In this study, *Botryosphaeria* was not an aggressive pathogen of even harshly treated sweetgum seedlings. In fact, inoculation had no significant effect on seedling development within any treatment. Cankers on seedlings after planting could not be attributed to stress during lifting and outplanting. The many cankers observed during the field survey of 1996 were probably correlated with environmental stress that winter and spring and were not an important contributor to the dieback.

The correlation between the spring flush and the subsequent dieback of transplanted seedlings (fig. 1) adds statistical support to the idea that delayed foliage production indicated seedling stress. This was an interesting but unplanned benefit of the present study and provides a degree of confidence to this early assessment for seedling or planting quality, or both.

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Appendix table 1—Treatments applied to sweetgum seedlings by Union Camp personnel in 1997. Each treatment below is applied both to operationally lifted and research optimally lifted seedlings.

2 levels of drying for roots; 0 or 20 minutes (0 = control).

2 Temperature exposures; 2 hours at 28 °C or 2 hours at 85 °C

2 levels of drying for tops; 6 hours or 12 hours

2 levels of anaerobic stress; 24 hours or 72 hours.

1 level Westvaco seedlings at 0 or 20 minutes root dry.

3 levels of inoculation[a]

1= wound plus sterile PDA
2= wound plus Botryosphaeria on PDA
3= wound plus Botryosphaeria plus Captan root dip @ 2.4 g ai/L

[a] The three inoculation treatments plus the 0 root drying are compared in table 3.

FUSIFORM RUST TRENDS IN EAST TEXAS: 1969 TO 2002

Dean W. Coble and Young-Jin Lee[1]

Abstract—Fusiform rust [*Cronartium quercuum* (Berk.) Miyabe ex Shirai f. sp. *Fusiforme*] infection rates in east Texas increased to nearly 50 percent in slash pine (*Pinus elliottii* Engelm.) and about 15 percent in loblolly pine (*Pinus taeda* L.) plantations during the 18-year period from 1969 to 1987. New data from the East Texas Pine Plantation Research Project showed that fusiform rust infection rates in slash pine peaked in 1987, then decreased to about 15 percent by 2002. For loblolly pine, the rates stabilized around 10 percent after 1987, then decreased to around 5 percent by 2002. The peak infection rates occurred circa 1987 when plantations were 8 to 11 years old. This 32-year continuous record of fusiform rust incidence in east Texas indicates that infection rates are relatively stable (about 10 percent) for loblolly pine and much greater (up to 50 percent) for slash pine.

INTRODUCTION

Fusiform rust is the most important disease affecting the approximately 2.5 million acres (Rosson 1995) of loblolly and slash pine plantations in east Texas (Adams 1989, Pye and others 1995). This disease can impact thinning schedules or rotation ages (Dinus and Schmidt 1977), or both, by reducing stocking levels (Adams and others 1996; Lee and Coble 2002a, 2002b; Nance and others 1981; Shoulders and Nance 1987; Wells and Dinus 1978), which then reduces potential revenues (Bridgwater and Smith 1997, Bridgwater and Smith 2002, Pye and others 1997).

Fusiform rust incidence surveys in east Texas are available from six surveys conducted between 1969 and 1990 (Hunt and Lenhart 1986; Lenhart and others 1988, 1994; Mason and Griffin 1970;Texas Forest Service 1982; Walterscheidt and Van Arsdale 1976). The first three studies presented average rust percentages for independent surveys, whereas the latter three combined the earlier survey data with data from the East Texas Pine Plantation Research Project (Lenhart and others 1985). In the last (sixth) east Texas survey, Lenhart and others (1994) reported that rust incidence in loblolly pine remained stable around 10 percent through 1990, whereas rust incidence in slash pine declined by 7 to 8 percent to 41 percent through 1990.

As of 2002, the ETPPRP consisted of 193 permanent plots located in loblolly and slash pine plantations throughout east Texas. Each plot has been remeasured on a 3-year cycle since 1984. The rust incidence data gathered at each remeasurement should provide forest managers with valuable insight into temporal trends of fusiform rust in east Texas pine plantations.

The purpose of this study is to report fusiform rust incidence trends in east Texas pine plantations for the years 1993, 1996, 1999, and 2002. This report represents the seventh rust survey for east Texas, thereby creating a contiguous 32-year record of fusiform rust incidence from 1969 to 2002.

METHODS

Currently, 132 permanent plots are located in loblolly pine plantations, and 61 plots are located in slash pine plantations throughout east Texas. The ETPPRP study area covers 22 counties across east Texas. Generally, the counties are located within the rectangle from 30 to 35 north latitude and 93 to 96 west longitude. Each plot consists of two subplots: one for model development and one for model evaluation. A subplot is 100 by 100 feet in size, and a 60-foot buffer separates the subplots. All planted pine trees are permanently tagged and numbered. At each remeasurement, each monumented tree was examined for the presence/absence of fusiform rust according to the following guidelines:

(a) Infected stem: Gall on a stem or a live branch within 12 inches of the stem.

(b) Infected branch: Gall on a live branch more than 12 inches from the stem.

Subsequent rust analyses were limited to plantations 5 years old or older because field crews could not reliably detect galls on pine trees less than 5 years of age. Stem rust incidence was calculated for each plot as the proportion of living trees with stem galls, irrespective of branch galls.

Rust infection data from the ETPPRP development plots were used for this survey (tables 1 and 2), as well as the 1984, 1987, and 1990 surveys. Two separate datasets for each species were constructed to examine rust incidence trends:

(a) All plots present in the current measurement cycle were analyzed as one-time observations to examine rust incidence at that moment in time.

(b) Original plots that remained intact (i.e., not destroyed) since the 1984 measurement cycle were analyzed to examine rust incidence trends for consecutive 3-year periods.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Table 1—Descriptive statistics for the ETPPRP loblolly pine development plots

Year	Variable	N	Mean	Standard deviation	Standard error	Minimum	Maximum
1984	TPA	78	453.9	141.2	16.0	148.0	849.0
	BA/A		51.3	35.8	4.1	0.0	116.0
	Age		9.2	3.1	0.3	5.0	17.0
	SI		65.3	13.9	1.6	27.0	95.0
1987	TPA	146	465.1	141.8	11.7	105.0	858.0
	BA/A		50.8	41.4	3.4	0.0	173.0
	Age		9.0	3.8	0.3	5.0	19.0
	SI		70.0	14.4	1.2	25.0	115.0
1990	TPA	170	475.9	149.6	11.5	87.0	998.0
	BA/A		68.0	39.1	3.0	4.0	183.0
	Age		10.8	3.8	0.3	5.0	21.0
	SI		69.3	12.5	1.0	35.0	105.0
1993	TPA	161	464.5	146.3	11.5	87.0	928.0
	BA/A		94.2	35.2	2.8	11.0	192.0
	Age		13.5	3.7	0.3	8.0	24.0
	SI		71.8	12.1	1.0	34.0	108.0
1996	TPA	151	448.9	141.8	11.5	87.0	906.0
	BA/A		114.5	34.4	2.8	12.0	189.0
	Age		16.2	3.7	0.3	10.0	27.0
	SI		70.3	10.2	0.8	33.0	92.0
1999	TPA	148	425.9	134.8	11.1	87.0	845.0
	BA/A		128.2	34.7	2.9	13.0	204.0
	Age		19.3	3.7	0.3	14.0	30.0
	SI		70.3	9.6	0.8	30.0	92.0
2002	TPA	132	397.1	130.1	11.3	30.0	780.0
	BA/A		136.8	36.8	3.2	9.0	220.0
	Age		22.3	3.7	0.3	17.0	33.0
	SI		71.9	10.8	0.9	31.0	134.0

ETPPRP = East Texas Pine Plantation Research Project; TPA = trees per acre; BA/A = basal area (ft^2) per acre; Age = plantation age; SI = site index (index age = 25 years).

RESULTS

Fusiform rust infection rates for loblolly pine have remained relatively stable around 10 percent since 1969, except in 1987 and 1990 (table 3). In 1987 and 1990, the rates increased slightly to a high of 15 percent. However, the rates decreased since that period to a low of 5 percent in 2002. The observed infection rate range of 5 to 15 percent over the 32-year period is lower than the range of 12 to 19 percent reported by Phelps (1977) for loblolly pine planted along the gulf coast, east of Texas. Lenhart and others (1994) reported that this phenomenon might be attributed to a lower mortality rate of infected east Texas loblolly pine trees coupled with fewer trees becoming infected.

Fusiform rust infection rates for slash pine have gradually decreased from the 40 percent range in 1987 to about 15 percent in 2002 (table 3). The largest drop occurred from 1999 (about 23 percent) to 2002 (about 15 percent). These infection rates more closely resemble the rate of 10 to 41 percent reported for slash pine in other Southern States (Phelps 1977) than those reported for 1987 (Lenhart and others 1988). This decrease is likely attributed to the death of infected trees because there are fewer infected trees in the proportion of total live trees for older plantations. A drought in the late 1990s may also have contributed to this decrease as infected trees died in response to water stress.

Fusiform rust infection rates remained higher for slash versus loblolly pine for all years. Slash pine trees are more susceptible to fusiform rust than loblolly pine trees and thus are more likely to die (Bridgwater and Smith 2002, Powers 1975). Slash pine not being native to east Texas may also contribute to the rate difference because trees planted outside their natural range are highly susceptible to disease (Little 1971). In any case, the highest infection rates for both species are reported for 1987 and 1990. In these years, plantations were 8 to 11 years old, which corresponds to the period when rust galls are prevalent and easily observed, but rust-induced mortality is minimal (Wells and Dinus 1978); i.e., susceptible young pine trees that are infected have not yet died, so the incidence of infection in the plantation peaks in this age range.

The fusiform rust trends in the original plots should provide deeper insight into how infection changes for specific plot locations. Of the original 78 loblolly and 40 slash pine plots established during the first (1984) measurement cycle in

Table 2—Descriptive statistics for the ETPPRP slash pine development plots

Year	Variable	N	Mean	Standard deviation	Standard error	Minimum	Maximum
1984	TPA	40	356.5	147.0	23.3	135.0	1002.0
	BA/A		35.6	29.2	4.6	0.0	107.0
	Age		8.6	3.0	0.5	5.0	16.0
	SI		72.6	15.1	2.4	30.0	108.0
1987	TPA	73	413.1	177.3	20.8	113.0	989.0
	BA/A		36.9	28.3	3.3	0.0	129.0
	Age		8.7	3.7	0.4	5.0	18.0
	SI		74.2	15.6	1.8	15.0	110.0
1990	TPA	76	388.3	176.4	20.2	113.0	923.0
	BA/A		53.5	28.0	3.2	1.0	140.0
	Age		11.0	3.8	0.4	6.0	21.0
	SI		74.9	12.6	1.4	22.0	96.0
1993	TPA	66	377.1	173.6	21.4	91.0	897.0
	BA/A		69.8	29.0	3.6	7.0	166.0
	Age		13.3	3.2	0.4	9.0	24.0
	SI		75.5	10.6	1.3	37.0	93.0
1996	TPA	65	346.3	160.3	19.9	78.0	758.0
	BA/A		84.4	31.3	3.9	16.0	133.0
	Age		16.2	3.1	0.4	12.0	26.0
	SI		75.4	10.0	1.2	37.0	94.0
1999	TPA	65	313.1	153.3	19.0	70.0	693.0
	BA/A		92.5	35.2	4.4	24.0	155.0
	Age		19.3	3.1	0.4	15.0	29.0
	SI		75.0	9.4	1.2	39.0	99.0
2002	TPA	61	286.7	151.0	19.3	61.0	662.0
	BA/A		98.8	39.3	5.0	24.0	168.0
	Age		22.2	3.0	0.4	18.0	33.0
	SI		73.8	8.4	1.1	41.0	91.0

ETPPRP = East Texas Pine Plantation Research Project; TPA = trees per acre; BA/A = basal area (ft^2) per acre; Age = plantation age; SI = site index (index age = 25 years).

Table 3—Average fusiform rust incidence (expressed as a percentage) in loblolly and slash pine plantations greater than 5 years old by survey year and geographic location in Texas

Species/ Location of rust galls	Survey year									
	1969	1976	1980	1984	1987	1990	1993	1996	1999	2002
					East Texas[a]					
Slash										
Stem only	8	—	—	35	41	33	26	27	22	14
Stem + branches[c]	—	30	—	45	44	37	29	34	24	16
Loblolly										
Stem only	6	—	—	8	11	10	7	9	8	5
Stem + branches	—	9	—	11	15	14	8	11	10	5
					Southeastern Texas[b]					
Slash										
Stem only	19	—	32	39	41	32	27	28	23	15
Stem + branches	—	43	55	47	44	36	30	36	25	17
Loblolly										
Stem only	—	—	8	10	13	11	9	9	9	6
Stem + branches	—	6	18	14	16	15	10	13	11	6

[a] Includes counties in southeastern Texas.

[b] Includes all counties located south of Cherokee, Angelina, San Augustine, and Sabine counties.

[c] May or may not also have rust-infected branches located greater than 12 inches from stem.

plantations greater than 5 years old, 43 loblolly and 20 slash pine plots remained in 2002. Fusiform rust infection trends for these "survivor" plots (table 4) did not substantially differ from those for all plots (table 3). The only exception might be for slash pine in 1999 and 2002. However, we believe the difference is attributable to sampling variation rather than an actual trend. This differs from the explanation of Lenhart and others (1994), who believed the difference was attributed to impact of younger slash pine plots with lower rust incidence on the average rate values calculated from all plots present in the measurement cycle.

CONCLUSIONS AND RECOMMENDATIONS

The 32-year continuous record of fusiform rust incidence in east Texas reported here indicates that infection rates are relatively stable (about 10 percent) for loblolly pine but much greater (up to 50 percent) for slash pine. The greatest period of infection incidence occurs when plantations are 8 to 11 years of age. If forest managers desire to produce sawtimber/plywood grade timber from their plantations, they should consider planting loblolly over slash pine or choose proven, rust-resistant slash pine planting stock. For existing slash pine plantations, forest managers should consider intensive silvicultural methods to reduce the impact of fusiform rust on wood quality. For short-rotation pulpwood plantations, the faster growth of slash pine may outweigh its high rust susceptibility. However, managers should realize slash pine is not native to east Texas and therefore expect high infection rates in slash pine plantations, unless proven rust-resistant slash pine planting stock is used.

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Table 4— Average fusiform rust incidence (expressed as a percentage) for original loblolly and slash pine plots established during the 1984 measurement cycle in plantations greater than 5 years old in East Texas

Species/ Location of rust galls	Survey year						
	1984	1987	1990	1993	1996	1999	2002
				East Texas[a]			
Slash							
Stem only	35	43	33	26	22	16	9
Stem + branches[c]	45	48	38	28	24	18	10
Loblolly							
Stem only	8	12	12	8	10	10	6
Stem + branches	11	17	18	9	12	11	6
				Southeastern Texas[b]			
Slash							
Stem only	39	44	32	25	22	17	10
Stem + branches	47	48	37	27	25	19	11
Loblolly							
Stem only	10	14	13	9	10	11	7
Stem + branches	14	19	19	10	12	12	7

Note: In 2002, 41 loblolly plots and 20 slash plots remained of the original 78 and 40, respectively.

[a] Includes counties in southeastern Texas.

[b] Includes all counties located south of Cherokee, Angelina, San Augustine, and Sabine counties.

[c] May or may not also have rust-infected branches located greater than 12 inches from stem.

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ICE DAMAGE IN A CHRONOSEQUENCE OF AGROFORESTRY PINE PLANTATIONS IN ARKANSAS, U.S.A.

David M. Burner and Adrian Ares[1]

POSTER SUMMARY

Potentially damaging ice storms are expected within the natural range of loblolly pine about every 6 years (Schultz 1997). The recovery of ice—damaged loblolly pine, particularly from stem bending, has not been well documented. The literature also is contradictory as to whether ice damage of loblolly pine is affected by tree spacing and thinning (Amateis and Burkhart 1996; Belanger and others 1996; Burton 1981), perhaps because of environmental differences (storm characteristics, topography, tree age, and management). Whether trees are in natural stands or plantations, ice damage is minimized when management fosters crown symmetry.

Acute (broken and leaning) and transient (bending) damage to loblolly pine were assessed in a case study of experimental agroforestry plantations following a late December 2000 ice storm. Stand ages were 7, 9, and 17 years old, and tree density ranged from 150 to 3,360 trees per ha in multirow and rectangular configurations. Agroforestry design influenced ice damage in 7-year-old stands, but no design had catastrophic loss. Wider tree spacing or lower stand density of 7-year-old trees increased stem breakage, whereas closer spacing increased bending. Most bent 7-year-old trees had straightened 8 months after the storm, and this recovery was determined more by degree of initial bend rather than height or diameter. Nine-year-old loblolly pine had 19 percent more top breakage and 59 percent more stem breakage than shortleaf pine. Thinning from above increased susceptibility of ice damage to a 17-year-old stand compared to a nonthinned stand. The case study supports the cultivation of loblolly pine in areas prone to ice damage. Better understanding of tree recovery improves poststorm management decisions.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

REFORESTATION EFFORTS IN INDIANA FOLLOWING THE SURFACE MINING CONTROL AND RECLAMATION ACT OF 1977

Stephen D. Fillmore and John W. Groninger[1]

Abstract—During the summer of 2002, data were collected from 22 post-Surface Mining Control and Reclamation Act sites in southwestern Indiana. Tree growth across these sites was generally poor, with site index values typically less than 40 feet (base age 50) for upland oaks. *Robinina pseudoacacia* (black locust) was observed to be the primary overstory tree throughout sites and was not acting as a nurse tree for other species. No specific mining or reclamation technique encountered in this study was associated with high site quality. Results of this study will be compared with more modern mining and reclamation techniques.

INTRODUCTION

The Surface Mining Control and Reclamation Act (SMCRA) of 1977 was promulgated to address environmental degradation resulting from abandoned surface mines. Topsoil handling provisions of SMCRA designed to prevent water quality impairment resulted in degraded growing media for trees. Soils on post-SMCRA reclaimed sites were typically compacted, nutrient poor, and droughty. Compaction resulted from multiple passes by reclamation machinery. Provisions of SMCRA designed to prevent erosion required mine operators to initially revegetate sites with dense ground covers such as *Festuca arundinacea* (reed fescue) or *Lespedeza cuneata* (Chinese lespedeza). Seedlings planted into these dense herbaceous covers experienced high mortality rates and poor growth. Browsing and suppressed growth led to poor crown form. The potential for forest products is low on the sites due to a lack of marketable stems. These factors have led to a decrease in the forest land base in southwestern Indiana. Prior to SMCRA, most abandoned mine sites were planted to trees, leading to an increase in forest land. After SMCRA, many sites were returned to low-value hay and pastureland, due in part to poor tree growth. This phenomenon has sparked concern from the Indiana Department of Natural Resources and the Office of Surface Mining that poor postmining tree performance contributes to a loss of forest cover in mining regions of the State.

This study was initiated to investigate the success or failure of post-SMCRA reforestation efforts in Indiana. During the summer of 2002, an inventory of 16 mines in Indiana was completed. Objectives included determining the principal factors driving tree-growth patterns, determining how these factors will affect the long-term stand dynamics, and developing recommendations for future reclamation and reforestation efforts.

METHODS

Twenty-two study sites on 16 mines in southwestern Indiana were inventoried. Transects were placed on sites, with random distances between plots generated in the field. Plots sized 1/735-acre were placed in a cardinal-eight direction plot layout. At each plot, overstory trees were identified, and height and diameter at breast height (d.b.h.) were measured. Percent cover of herbaceous vegetation was estimated by species at every plot. Position of plots in either an upland or a bottomland was recorded, as well as slope percent and aspect.

RESULTS AND DISCUSSION

A total of 1,280 plots were inventoried across 22 study sites; 2,847 trees were inventoried for height, and 2,141 were inventoried for d.b.h. *Robinia pseudoacacia* (black locust) was the most frequently occurring tree species in the inventory, comprising 45 percent of the stems on sites. Commonly occurring volunteer species included *Platanus occidentalis* (American sycamore), *Acer rubrum* (red maple), and *Prunus serotina* (black cherry). All but four sites were found to be adequately stocked. Stem density ranged from 2,919 to 115 trees per acre, with a mean of 1,119. Basal area ranged from 78.28 to 1.4 square feet per acre, with a mean of 25.6.

The principal herbaceous species recorded on the study sites was *Festuca arundinacea* (reed fescue), a widely-planted cool season grass. *Solidago canadensis* (Canada goldenrod), a volunteer herbaceous species, was the second most commonly occurring herbaceous species. The suitability of sites for forest products production was low. Site indices for the study sites averaged 40 feet at age 50, with a maximum of 65 feet at age 50. Little potential for forest products production exists on these sites beyond *R. pseudoacacia* for firewood.

Potential of sites for carbon capture value was also analyzed. Because site productivity is low on the study sites, current potential carbon market value was also low. The mean carbon capture total rate on sites was 1.36 tons of carbon per acre. The highest total carbon capture rate observed was 3.89 tons of carbon per acre. Potential for carbon capture rates may be increased in the future due to the succession from *R. pseudoacacia* overstories toward fast-

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

growing, light-seeded volunteer hardwood tree species. Silvicultural management of these lands may also increase product values.

Plots classified as being in an upland position resulted in significantly higher mean tree heights. Trees in this position tended to be of planted origin and were likely older than stems in the bottomland position.

CONCLUSIONS AND RECOMMENDATIONS

Study sites are moving away from early dominance by planted *R. pseudoacacia* towards a state similar to old field succession. *R. pseudoacacia* is subject to decline due to damage from the locust borer. The locust borer attacks stems and twigs of trees and reduces the crown dominance. This process is creating gaps in the overstory that volunteer species are claiming. These volunteer species are expected to comprise the majority of the overstory within the next 30 years, if stands are left unmanaged.

Growing conditions on post-SMCRA reclaimed sites would have been more favorable if the growing media had not been compacted. Fortunately, this has been recognized by the industry, and compaction-causing equipment such as scrapers are no longer used. Results from this study suggest that stands are being affected primarily by edaphic conditions. No vegetative interactions analyzed resulted in significant differences.

Proper species selection and recognizing soil changes associated with mining-related soils handling will aid in improving forest productivity on post-SMCRA mined sites. This will also restore more quickly and effectively the look and function of a forest to surface mined sites.

BASELINE CHARACTERIZATION OF FORESTED HEADWATER STREAM HYDROLOGY AND WATER CHEMISTRY IN SOUTHWEST GEORGIA

David G. Jones, William B. Summer, Masato Miwa, and C. Rhett Jackson[1]

Abstract—Stream hydrology and water quality in headwater streams are important components of ecosystem health. The Dry Creek Long-Term Watershed Study is designed to evaluate the effects of upland forestry operations and stream management zone (SMZ) thinning on stream hydrology, water quality, benthic macroinvertebrates, and other biologic indicators. The study also tests the effectiveness of Georgia Best Management Practices (BMP). The study was established in the Spring of 2001 and monitors four adjacent first-order stream watersheds that range in size from 26 to 48 ha. Monthly grab samples and stormflow samples were taken and analyzed for nitrate/nitrite (NO_3^-/NO_2^-), ammonium (NH_4^+), total nitrogen (TN), ortho-phosphate ($O\text{-}PO_4^-$), total phosphorus (TP), and total suspended solids (TSS). Preliminary water quality analysis indicated that nutrient concentrations fluctuate seasonally with similar trends among watersheds. However, nutrient concentrations during storm events are highly variable with very few consistent trends.

INTRODUCTION

Understanding stream hydrology and water quality in a forest ecosystem is critically important to evaluate how forest management practices affect ecosystem health. This is especially true in headwater systems where terrestrial and aquatic ecosystems interact closely. First- and second-order streams comprise nearly three quarters of the total stream length in the United States (Leopold and others 1964), yet effects of human disturbance on these vital components of watershed and ecosystem health are not well documented. Improving knowledge of headwater stream response to forest management is especially important in the southeast where forestry encompasses over 215 million acres (Wear and Greis 2002) and almost 40 percent of the nations forestland (FAO 2001).

This paper describes baseline hydrology and water quality conditions in small, relatively undisturbed headwater systems during the pretreatment period of a long-term watershed study. Discussion includes: (1) seasonal variation in nutrient concentrations, (2) nutrient behavior during storm events, and (3) relationships between nutrients and watersheds.

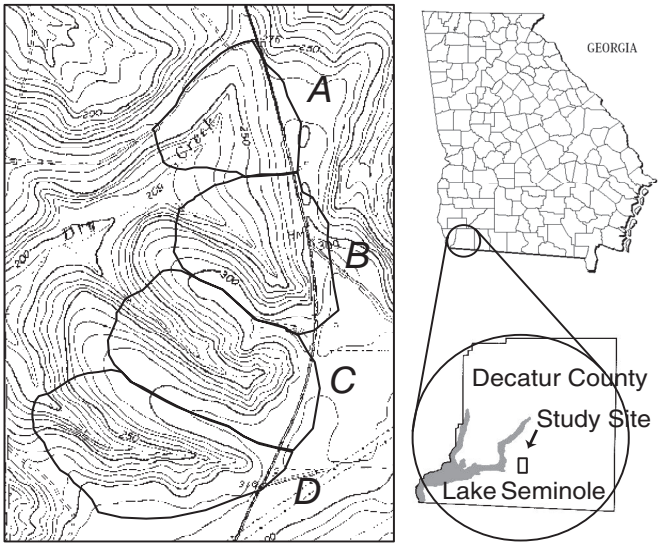

Figure 1—Study site (left), study location (right).

METHODS

Study Site

The study watersheds are located on International Paper's Southlands Forest in the southwest corner of Georgia (fig. 1). The study lies on the Pelham escarpment between the Tifton Upland and the Dougherty Plain found within the Coastal Plain physiographic region. The soils are predominately well-drained Ultisols with sandy surfaces. The Esto series comprises the riparian area of all 4 watersheds. The slopes are Eustis series soils with the Wagram, Lakeland, Norfolk and Orangeburg series comprising a majority of the upland soils (Soil Survey Report 1980). The streams in this study drain four adjacent watersheds with similar aspect, size, shape, soils and vegetative cover type. One of the few apparent differences is the valley floor geometry. Watersheds A and B have broad, flat valleys with riparian wetlands while watersheds C and D have more channelized streams running through steeper, v-shaped valleys (Summer 2003).

Study Design

The overall statistical study design is a completely randomized design with two replications. The control watersheds are A and D, and the treatment watersheds are B and C (fig. 1). The control will receive no silvicultural treatment for the duration of the study. The treatment watersheds will be clearcut with the exception of an SMZ; each SMZ will be divided into an upper and lower section. An undisturbed SMZ treatment will be located at the upper section of the

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

stream, and a partially harvested SMZ treatment will be located at the lower section of the stream. The partially harvested SMZ's will be thinned in accordance with Georgia BMP's, which require a minimum of 50 percent canopy cover or a residual 50 square feet of BA, evenly distributed. Treatments will be installed in the Fall of 2003.

Data Collection

Automated stream monitoring stations are located at the outlet of each watershed (four sites) and at the lower boundary of the upstream SMZ treatment (two sites). Stream stage and discharge is recorded every 15 minutes by Isco Model 4230 Bubbler Flow Meters. An Isco Model 6712 automated sampler collects seven water samples starting at the beginning of stormflow on 15 minute intervals. Monthly in-situ measurements and grab samples are taken from a downstream and midstream location within each watershed as well as at an upstream boundary-line location in the B & C watersheds. Data presented in this paper include monthly grab samples and in-situ pH measurements between October 2001 and November 2002 and 13 storm events during the same period. All water samples were analyzed for NO_3^-/NO_2^-, NH_4^+, TN, $O\text{-}PO_4^-$, TP, and TSS.

Methods of Analysis

Inorganic nutrient concentrations were determined with a Lachat (Milwaukee, WI) Quikchem 8000 using a flow-injection colorimetric method (Lachat Instruments 2001). In-stream measurements of pH were determined using an OAKTON (Vernon Hills, IL) pHTestr 2. TN and TP concentrations were determined with a CEM (Matthews, NC) MDS-2000 using a persulfate microwave digestion method (Johnes and Heathwaite 1992). TSS were determined by filtering a known volume of homogenized sample onto preweighed glass fiber filters [Gelman (Ann Arbor, MI) A/E, 1 µm], dried and reweighed. A Pearson's correlation analysis was conducted to determine correlations between variables within watersheds and correlations between like variables in different watersheds (SPSS Inc. 1997). Variable correlation plots were constructed based on two highest principle component scores of variables for each watershed (MINITAB Inc. 1996).

RESULTS AND DISCUSSION

Temporal Change in Nutrient Concentrations

In this section, we discuss Watershed B data to illustrate the general trends exhibited by all four watersheds. Monthly grab sample NO_3^-/NO_2^- concentrations indicated seasonal trends and consistent spatial relationships. The fluctuation patterns of NO_3^-/NO_2^- were similar for all sampling sites within the stream, and concentrations decrease from upstream to downstream (fig. 2). Similar fluctuation patterns of NO_3^-/NO_2^- at the three sites within the stream may indicate stable groundwater inputs and soil nitrate processes. The concentration decrease from upstream to downstream could have been caused by assimilative reduction (organism uptake), denitrification, and leaching. Several studies have shown that one, if not all, of these processes play an important role in the N removal process of Coastal Plain riparian forests (Ambus and Lowrance 1991, Correll and others 1994, Hendrickson 1981, Jacobs

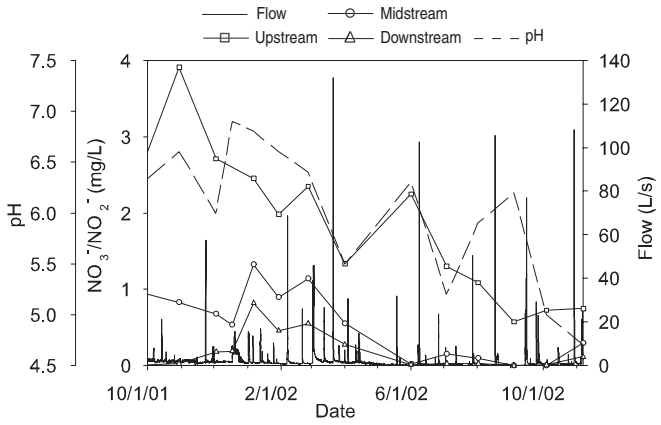

Figure 2—Seasonal fluctuations of monthly grab sample NO_3^-/NO_2^- and pH in the B-Watershed with the corresponding hydrograph for that period.

and Gilliam 1985, Jordan and others 1993, Lowrance 1992, Lowrance and others 1984). NO_3^-/NO_2^- concentrations were also higher during the dormant season compared to the growing season. Seasonal fluctuation of NO_3^-/NO_2^- concentrations has been observed in many other studies (Owens and others 1991, Pionke and others 1999) showing that soil moisture often shifts from a growing season deficit to a dormant season excess causing the remobilization of excess soil NO_3^-/NO_2^-. Temporal fluctuations of NO_3^-/NO_2^- generally followed a similar pattern as the pH. This could be due to the relationship between anion exchange capacity and pH, with fewer nitrates being exchanged in the soil as the pH increases, thus allowing more nitrates to move in solution (Bellini and others 1996, Qafoku and others 2000).

Monthly grab sample NH_4^+ concentrations had similar fluctuation patterns for all sampling sites within the stream (fig. 3). The upstream site had the lowest NH_4^+ concentration; the highest concentrations were recorded at the midstream site. NH_4^+ concentrations were, on average, higher during the growing season than in the dormant season.

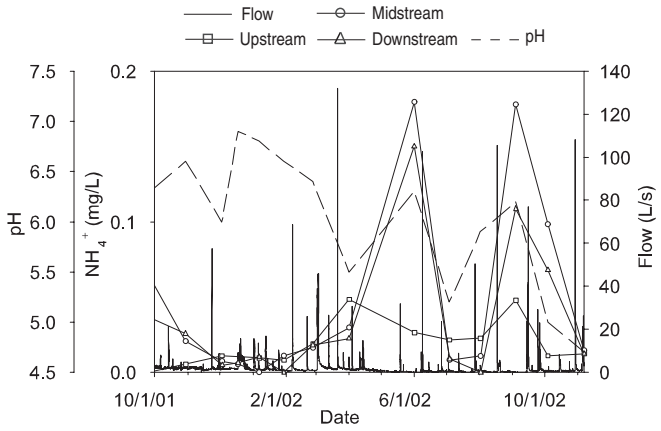

Figure 3—Seasonal fluctuations of monthly grab sample NH_4^+ and pH in the B-Watershed with the corresponding hydrograph for that period.

Similar NH_4^+ temporal fluctuations have been observed in other studies (Verchot and others 1997). This could be caused by increased mineralization as the riparian soil environment becomes more aerobic during the growing season. The NH_4^+ appeared to have a weaker relationship with pH compared to the relationship between NO_3^-/NO_2^- and pH.

Monthly grab sample $O\text{-}PO_4^-$ concentrations had similar fluctuation patterns for all sampling sites within the stream, and the concentrations generally increased from upstream to downstream (fig. 4). $O\text{-}PO_4^-$ concentrations were, on average, higher during the growing season than in the dormant season. Seasonal fluctuations of $O\text{-}PO_4^-$ concentrations have been observed in many other studies (Gburek and Heald 1974, Mulholland and Hill 1997, Pionke and others 1999). This could be explained in part by the relationship between P sorption capacity and saturated soil conditions. Holford and Patrick (1979) have shown that P sorption capacity of an oxidized soil can increase during periods of saturation and reduction due to the formation of amorphous ferrous hydroxides, which have a greater surface area and more sorption sites than the more crystalline, oxidized, ferric forms. This process may explain why there were lower concentrations of $O\text{-}PO_4^-$ in solution during the dormant season when the soil in these riparian areas was saturated. The $O\text{-}PO_4^-$ fluctuation appeared to have a weak inverse relationship with pH.

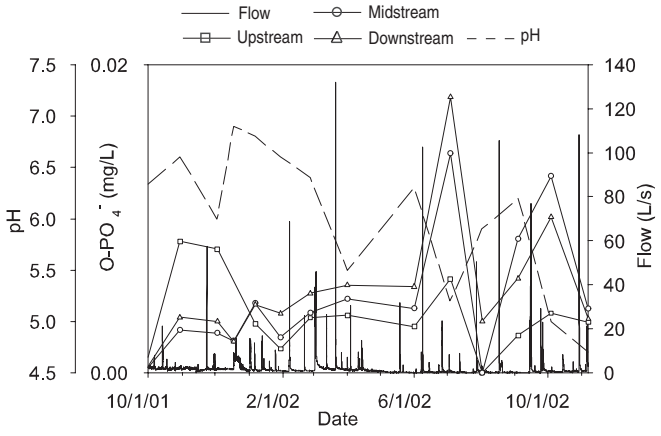

Figure 4—Seasonal fluctuations of monthly grab sample $O\text{-}PO_4^-$ and pH in the B-Watershed with the corresponding hydrograph for that period.

Stormflow Nutrient Concentrations and Correlations

Concentrations from 15-minute sampling during storm events varied by event and season with few consistent trends; some decreased, increased, or remained approximately equal as flow increases. Additionally, nutrient levels occasionally spiked at varying times in an event. A combination of these characteristics made it difficult to predict nutrient concentrations and flow relations. In order to analyze the data, average nutrient concentrations for an event were calculated from seven 15-minute storm samples and were compared to determine any correlations within and between watersheds.

In general, inorganic nutrients were poorly correlated to other nutrient concentrations within watersheds. However, TN, TP, TSS, and flow were relatively well correlated within watersheds. The Pearson correlations for Watershed C are shown in table 1 as an example, although correlation characteristics were similar within all four watersheds. Correlations between control and treatment watersheds for inorganic nutrient concentrations were poor for like nutrients with the exception of $O\text{-}PO_4^-$ between watersheds A-B and C-D. TP, TSS, and flow were relatively well correlated

Table 1—Pearson correlation of variables within watershed C

		NH_4^+	TN	$O\text{-}PO_4^-$	TP	TSS	Flow
NO_3^-/NO_2^-	r^2	0.207	0.066	-0.567	-0.395	-0.427	-0.028
	P	0.541	0.855	0.069	0.259	0.190	0.934
NH_4^+	r^2		-0.377	0.007	-0.495	-0.407	-0.198
	P		0.284	0.982	0.145	0.214	0.560
TN	r^2			-0.276	0.875	0.814	0.712
	P			0.440	0.001	0.004	0.021
$O\text{-}PO_4^-$	r^2				-0.002	0.009	-0.149
	P				0.996	0.979	0.662
TP	r^2					0.918	0.569
	P					<0.001	0.086
TSS	r^2						0.773
	P						0.005

NO_3^-/NO_2^- = nitrate/nitrite; NH_4^+ = ammonium; TN = total nitrogen; $O\text{-}PO_4^-$ = orthophosphate; TP = total phosphorus; TSS = total suspended solids.

between watersheds, with TN being somewhat less related (table 2). These results may indicate that concentrations of inorganic nutrients are highly influenced by dynamic environmental factors that control biogeochemical processes, such as temperature, soil moisture, pH, microbial activity, etc., while total nutrient concentrations are more stable.

Variable correlation plots showed similar relationship trends between control watershed A and treatment watersheds B & C. TN, TP, and TSS were closely located in all three watersheds (fig. 5). Additionally, NO_3^-/NO_2^- and NH_4^+ in watersheds A & B are somewhat negatively related to flow. Control watershed D had somewhat different nutrient relationships. The NH_4^+, $O\text{-}PO_4^-$, and TN were relatively well correlated, and there was some relationship shared between TP, TSS, and flow.

The between watershed correlation analysis indicated that the TN, TP, and TSS of the treatment watersheds could be predicted from like nutrients of the control watersheds. Furthermore, high correlations between TN, TP, and TSS within watersheds may strengthen predicting equations through the addition of highly correlated variables, a relationship which can be seen in the orientation of nutrients on the variable correlation plots. A more detailed analysis of the data may illustrate trends and correlations that were not observed in this analysis.

CONCLUSIONS

The patterns and trends of nutrient concentrations observed in these headwater streams appeared to be representative of what other studies have found under similar circumstances. Variations in grab sample inorganic nutrient concentrations exhibited trends that have been relatively well documented; yet detailed analysis showed inorganic nutrient stormflow concentrations were poorly correlated. However, total nutrient stormflow concentrations had very high correlations. This may suggest that the relatively stable total nutrient concentrations can be used for more long-term monitoring of nutrient trends and the more dynamic inorganic nutrient concentrations can be used for short-term process oriented studies.

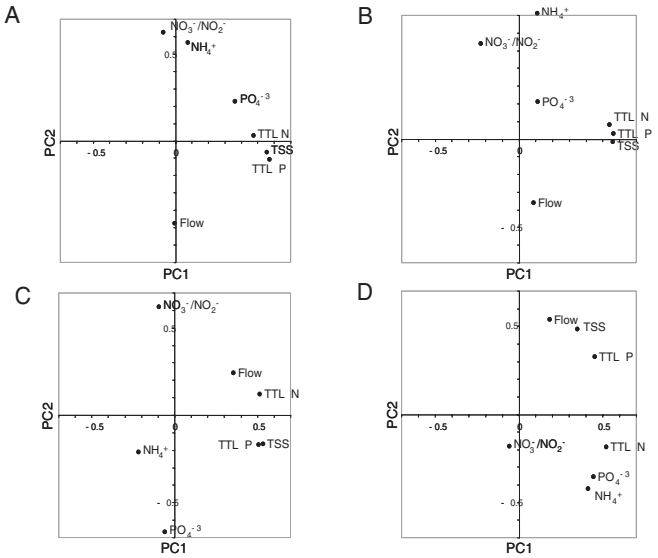

Figure 5—Variable correlation plots based on a principle component analysis for the four watersheds.

ACKNOWLEDGMENTS

The National Council for Air and Stream Improvement, International Paper, J.W. Jones Ecological Research Center, and the Georgia Forestry Commission are responsible for funding and support of the project. William B. Summer is responsible for a majority of the data collected that was presented in this paper.

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Table 2—Pearson correlation between control watersheds and treatment watersheds for NO_3^-/NO_2^-, NH_4^+,TN, $O\text{-}PO_4^-$,TP, TSS, and flow

		NO_3^-/NO_2^-	NH_4^+	TN	$O\text{-}PO_4^-$	TP	TSS	Flow
A - B	r^2	0.193	-0.174	0.828	0.740	0.578	0.802	0.874
	P	0.528	0.570	0.002	0.004	0.062	0.002	< 0.001
A - C	r^2	-0.310	-0.195	0.543	-0.021	0.782	0.445	0.922
	P	0.354	0.565	0.105	0.952	0.008	0.171	< 0.001
D - B	r^2	0.672	0.417	0.634	-0.001	0.921	0.781	0.919
	P	0.033	0.230	0.126	0.999	0.003	0.013	< 0.001
D - C	r^2	0.644	0.103	0.127	0.838	0.932	0.870	0.839
	P	0.061	0.791	0.787	0.005	0.002	0.002	0.005

NO_3^-/NO_2^- = nitrate/nitrite; NH_4^+ = ammonium; TN = total nitrogen; $O\text{-}PO_4^-$ = ortho-phosphate; TP = total phosphorus; TSS = total suspended solids.

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USE OF AERIAL HYPERSPECTRAL IMAGING FOR MONITORING FOREST HEALTH

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Abstract—This project evaluates the effectiveness of aerial hyperspectral digital imagery in the assessment of forest health of loblolly stands in central Alabama. The imagery covers 50 square miles, in Bibb and Hale Counties, south of Tuscaloosa, AL, which includes intensive managed forest industry sites and National Forest lands with multiple use objectives. Loblolly stands on upland sites within this area have a history of decline, root deterioration, and periodic severe southern pine beetle infestations. Forest Health Monitoring plots have been established throughout Alabama and other Southern States within the loblolly ecosystem. Additional Evaluation Monitoring (EM) plots are also established in the hyperspectral imagery assessment area. The database of the EM plots provides detailed information on soils, tree crown indicators of decline conditions, and root health/root pathogen interactions. The EM data provides reference points for the hyperspectral imagery.

INTRODUCTION

This hyperspectral imaging project is an extension of a Forest Health Monitoring assessment of loblolly pine (*Pinus taeda L.*) decline in central Alabama and a cooperative effort of the USDA Forest Service-Forest Health Protection Field Office in Pineville, LA, and Eastman Kodak Company, Rochester, NY. Loblolly decline has been prevalent on upland sites on the Oakmulgee Ranger District located predominately in Bibb, Hale, Perry and Chilton counties for the past 40 years. Periodic southern pine beetle epidemics and the district's reforestation efforts have gradually replaced a number of the declining stands with longleaf pine (*Pinus palustris Mill*), which is more suited for these sites.

The symptoms of loblolly decline are thinning of crown foliage and reduced radial growth, with mortality occurring within the 40- to 50- year age class. The Evaluation Monitoring (EM) data show that loblolly decline is a complex of biological events and site conditions that include: deterioration and necrosis of fine roots (Hess and others, in press), insect feeding, and vectoring of stain fungi of (*Leptographium spp.*) on primary roots (Eckhardt and others 2003), occurring on upland sites specific to loblolly host. Because the deterioration of fine roots precedes the expression of crown symptoms, hyperspectral imaging may be a useful tool for identifying the early stages of the decline complex. Hyperspectral imaging obtains a complete spectrum of electromagnetic radiation reflected from the earth's surface. The spectral range of 0.380 μm to 2.5 μm is optimal for forestry applications. The value of hyperspectral imaging over multispectral imaging is the ability to utilize the medium to fine scale spectral structure to monitor forest health.

Hyperspectral sensors provide the ability to detect discrete spectral changes while providing an airborne perspective needed for landscape level applications. Ground truth samples from tree crowns were measured with an Analytical Spectral Devices (ASD) field spectrometer during and 2 weeks after acquisition of the HYMAP imagery. Five categories of crown condition were initially identified representing the stages of decline. For this project, our objectives were to (1) evaluate the effectiveness and accuracy of hyperspectral products as a tool for monitoring forest health and detecting pest risk sites, and (2) determine the feasibility of hyperspectral products in forest management. Finding if hyperspectral measurements would aid in detecting a pre-visual stress of conifer stands was of specific interest.

METHODS AND PROCEDURES

Three flight lines 14 miles (22.5 km) long and 1.4 miles (2.3 km) wide, with 10-percent overlap, were established. Flight lines included 9 EM plots established to assess loblolly decline. Image data were collected September 2002 using Hyvista's hyperspectral mapping (HYMAP) instrument with a 5 m per pixel ground resolution. The spectral resolution was nominally 15 nm over the 0.380 μm to 2.500 μm spectral measurement range. Out of 126 bands collected, 115 were used in the analysis. Bands that were not detecting the surface were removed from analyses. The image data were calibrated to apparent reflectance.

Spectral measurements were collected on the ground, along with GPS coordinates, to register and calibrate airborne HYMAP images. Additionally, ground spectral measurements were acquired from 5 classifications of loblolly decline on EM plots to include: (1) Healthy – using FHM tree crown classification; (2) Pre-decline, defined as looking healthy from both the air and ground but under stress (e.g., fine root deterioration and reduced radial growth); (3) Decline, looks healthy from the air but is symptomatic when ground checked; (4) Fading, symptomatic from both the ground and the air; and (5) Dead with needles attached. Branch samples from each of the 5 classifications were taken and formed into a measurable crown shape. Ground spectral measurements sampled multiple examples of each classification found across all three flight lines. A primary objective of the ground measurements was to determine if foliar spectral differences could be detected

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

in the 5 classes. Ground measurements also determined if the field results were spatially scalable to that of the HYMAP images.

Spectral measurements were also taken of other forest species, soils, and other surface materials to define the background spectral clutter not part of loblolly decline. Other forest types/species included longleaf pine, upland hardwoods, and bottomland hardwoods. Additional measurements included open fields, kudzu, cutover forest-brush, concrete, asphalt, and soils. The final classification requirement was to detect the decline condition independent of the spectral background clutter.

Two separate sets of ground truth data were collected. One set was used as training and the second for accuracy assessment. The first set included areas on Forest Service land, mostly homogeneous over several pixels and in flight line 2 of the HYMAP data set. The training areas included 16 areas of healthy forest and 7 areas of loblolly pine decline. Most of the damaged areas were of class types predecline and decline. By localizing the training data to a single flight line, the classification could be assessed over the broader range of spectral measurement variability encompassed by all three flight lines.

The second data set consisted of 60 regularly spaced field plots covering all 3 flight lines. For each plot, the forest type and condition classes were recorded using USDA Forest Service Region 8 Silvicultural Handbook codes. The 60 field plots were also classified as damaged or healthy based on a visual crown rating. It was not possible to determine the predecline class in these plots except for the EM plots.

A number of algorithms were evaluated by Kodak's hyperspectral group to maximize detection of loblolly decline including maximum likelihood classification, spectral angle matching, spectral mixture analysis, multi-layer feed forward neural network, and linear finite impulse response (FIR) filters. This report focuses on the results from FIR filters because these came closest to meeting the combined set of objectives. Other studies have demonstrated the use of filters (Gruninger and others 2001, Pinzon and others 1998). Unique to this study was relaxing the filter constraints over the rigid constraints of previous studies. Specifically, a hyperspectral forest health index (HFHI) is presented that is based on a single FIR filter. This filter is specific to loblolly pine stands.

RESULTS

It was possible to uniquely detect the five classes of loblolly decline with no error using only the ground spectral measurements. Five separate FIR filters (one filter for each class) could perfectly separate over 40 spectral measurements per class taken at multiple-look angles of the different stages of decline. However, we were unsuccessful in applying the same FIR filters determined from ground measurements to the spatial scale of the HYMAP image measurements. In addition, we were unsuccessful in finding a completely separate set of filters that could be used to classify the five classes of decline. Clearly, there were foliar differences, but these were not detectable at the spatial scale of the HYMAP images.

We succeeded in creating a FIR filter from the training data to separate healthy from predeclined and declined loblolly trees. The classified output product, figure 1, was derived from the HFHI image. Although the filter was trained with data from flight line 2 (the middle strip in the mosaic), the results demonstrate the ability of the filter to perform consistently under varying cross track path radiance indicated by 0.800μm bandpass in figure 2. Similar variability existed in all HYMAP bandpasses.

For the 60 field plots, the classification of forest health (damaged and healthy) resulted in an overall classification accuracy of 83.3 percent (table 1). Correct classification of 72.2 percent of the plots judged damaged and 88.1 percent of the plots judged healthy was achieved. The classification is sensitive to geo-referencing due to the small local pockets of loblolly decline and the accuracy of the handheld GPS units (± 10 m). The plot sizes used for accuracy assessment were not much larger than a single 5-m- imaged pixel on the ground. A few sparsely spaced loblolly pines in mixed hardwoods are a difficult problem to detect especially when the imaged spatial resolution is typically larger than a single loblolly crown. Classification

Figure 1—Classified image derived from the hyperspectral forest health index (HFHI). Bright areas signify areas of loblolly decline whereas darker areas signify healthy vegetation. Note that the lands managed for timber production in the upper right indicate much less decline than those of the Forest Service lands in the middle to lower left. The distribution of decline is speckled in the image and

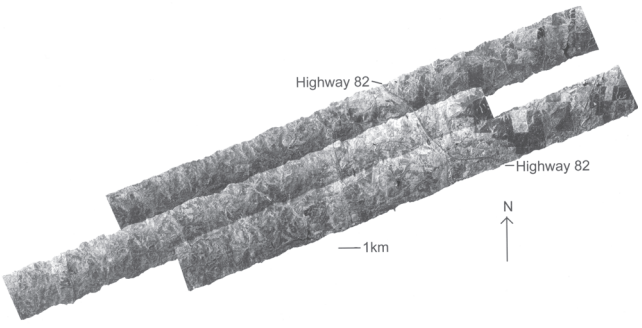

Figure 2—A mosaic of the three flight lines of the 0.800mm bandpass illustrates the spectral variability in cross track path radiance. Noticeable is a varying specular component from the forest also in the cross track scan direction. Training of the HFHI filter is performed specifically to be immune to small variations in calibration, specular reflectance, and path radiance.

Table 1—Hyperspectral classification of plot data

PID	St	FL	HFHI	Err	PID	St	FL	HFHI	Err	PID	St	FL	HFHI	Err
A3	H	1	108		A64-S2	H	1	135		A91	H	2	134	
A10	H	1	145		A66	H	1	202	E	A92	D	2	90	E
A21	H	1	156	E	A66-S1	H	1	104		A102-S1	H	2	110	
A22	H	1	77		A68	H	1	107		A108	D	2	148	E
A22-S1	H	1	129		A77	H	1	95		A109	D	2	168	
A22-S2	H	1	126		A79	H	1	105		A111	H	2	122	
A28	H	1	84		A80	H	1	113		C4	D	2	182	
A33	D	1	161		A81	H	1	152	E	C5	D	2	165	
A34	D	1	69	E	A83	H	1	131		C17	D	2	163	
A35-S1	D	1	145	E	A107	H	1	110		C18	D	2	191	
A36	H	1	131		C14	D	1	151		GS-2	H	2	144	
A41	H	1	74		C73	D	1	162		A28-S1	H	3	139	
A47	H	1	164	E	C73-S1	H	1	113		A82	H	3	121	
A50-S1	H	1	113		GS-1	D	1	153		A82-S1	D	3	161	
A51-S1	H	1	110		A52-S1	H	2	166	E	A94	D	3	158	
A51-S2	H	1	107		A55-S1	H	2	101		A93	H	3	106	
A52	H	1	98		A78	D	2	156		A97	H	3	68	
A61	H	1	76		A79-S1	D	2	198		A100	H	3	143	
A62	H	1	103		A88	H	2	127		A104	H	3	125	
A64-S1	H	1	28		A90	D	2	131	E	C39	H	3	140	

The plot ID (PID), health status (St with conditions of H healthy, D decline), flight line (FL), hyperspectral health index (HFHI) and error (Err) is recorded for each of the 60 plots. An HFHI value above 150 indicates a loblollystand class type to be pre-decline to decline. A value less than or equal to 150 indicates a healthy or other type of surface. Errors are delineated with an E in the Err field.

accuracy is significantly degraded given the potential for single-pixel, geo-referencing errors. For the most part, the errors in classification were made with HFHI values near the class boundary (e.g., values of 150), and these errors are within the uncertainty level of the filter. However, three plots (A34, A66, and A92) had HFHI values that were much larger than the filter uncertainty level. In rechecking these plots, both A34 and A92 were classified correctly by the filter but were near boundaries making them sensitive to GIS positioning errors. A66 was in a plot of 6 healthy longleaf pines surrounded by a stand of declining loblolly pines. It is likely that the filter performance decreases for area sizes near the image spatial resolution.

The HFHI filter is not directly detecting damage as a specific foliar spectrum. Filters derived from foliage using the field spectrometer measurements did not correspond to the image measurements, taking into account calibration and atmospheric uncertainty. It is unlikely that hyperspectral measurements can be used to differentiate a series of forest damage classes specific to loblolly decline due to the low signal to clutter ratio between healthy and declined stands. As the filter is linear, the training works well outside the training area as long as the surface components are spectrally similar.

Attempts to reduce the spectral resolution or range resulted in lower accuracies, indicating the significance of medium- to fine-scale spectral measurements unique to hyperspectral systems such as HYMAP. The spectral complexity of healthy canopies and those in decline, along with atmospheric variability, required the full spectral range of the HYMAP instrument to optimize detection of forest health classes.

CONCLUSIONS

A single FIR filter achieved an accuracy of better than 83 percent to detect a class defined by loblolly pine with both previsual and visual decline. Hyperspectral measurements were required to detect and map areas of loblolly decline. Attempts to reduce the spectral resolution resulted in significantly lower classification accuracies. We postulate that discrimination of decline is due to the scattering affects of the forest stand components (healthy needles, chlorotic needles, cones, branches, and bark) controlled largely by the crown geometry.

ACKNOWLEDGMENTS

This study was funded by Eastman Kodak.

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EFFECTS OF ARTIFICIAL DEFOLIATION ON THE GROWTH OF COTTONWOOD: SIMULATION OF COTTONWOOD LEAF BEETLE DEFOLIATION

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Abstract—*Populus* are among the fastest growing commercial forest trees but are not without problems. Insects and diseases can take their toll. The cottonwood leaf beetle (*Chrysomela scripta* F.; CLB) is of concern. Although damage by the CLB can result in terminal dieback, reduction in growth, and potential mortality, the impact on *Populus* growth and biomass accumulation is relatively scarce. This study was conducted near Cruger, MS, in a 2-year-old *Populus* plantation that had red oak seedlings interplanted. To assess the impact of CLB defoliation, varying levels of defoliation were applied during 2000. Defoliation at all levels had a significant effect on height growth. On average, undefoliated trees were significantly taller than defoliated trees. Trees defoliated at the rates of 50 percent and 75 percent exhibited the greatest decrease in growth. Height growth for trees defoliated at these levels was reduced by 30 and 31 percent, respectively. Trees defoliated at 25 percent were reduced in growth by 24 percent when compared to controls.

INTRODUCTION

Populus spp., some of the fastest growing commercial forest trees in North America with rotations of 6 to 12 years on good sites, grow well on the alluvial soils of the Lower Mississippi Alluvial Valley (LMAV). Uses of *Populus* range from wood products, fiber (pulp), and biomass energy to carbon sequestration. However, *Populus* are not without problems. Insects and diseases can take their toll on the cultivation of these trees. The primary insect pest of concern is the cottonwood leaf beetle (*Chrysomela scripta* F.), CLB. The CLB is a defoliator, with adults and larvae feeding on the young leaves and shoots of *Populus* species (Harrell and others 1982). Heavy feeding damage by the CLB can result in terminal dieback, reduction in growth (height, diameter), and potential mortality in young cuttings (Caldbeck and others 1978, Fang and Hart 2000).

Exact estimates of CLB defoliation impacts on *Populus* growth and biomass accumulation are relatively scarce. Bassman and others (1982), working on hybrid *Populus* in Wisconsin, found that moderate levels of artificial defoliation, mimicking CLB defoliation, had minimal effect on growth. However, severe levels of artificial defoliation caused marked decreases in height and diameter. Reichenbacker and others (1996) observed similar patterns, with *Populus* height, diameter, and aboveground biomass decreasing with increasing levels of defoliation. In the LMAV, comparable research on the impact of CLB defoliation on *Populus* is lacking. Information on CLB defoliation thresholds is needed because of the potential economic interest and impact that exists for *Populus* propagation in this region. The intent of this project was to determine the effects of artificial defoliation, designed to mimic the natural defoliation patterns of CLB, on the growth of *Populus* in a plantation setting within the LMAV.

SITES

This study was conducted in a 2-year-old *Populus* plantation in Leflore County near Cruger, MS. The plantation had been interplanted with red oak seedlings (*Quercus* spp.) and is enrolled in the Wetlands Reserve Program, with the intent of restoring a bottomland hardwood forest to this site.

PROCEDURES

Artificial Defoliation

To assess the impact of CLB defoliation, we applied varying levels of artificial defoliation to *Populus* during spring and summer 2000. We established 2 plot sizes within the plantation, small plots consisted of blocks of 4 trees, and large plots consisted of blocks of 16 trees. Treatments applied to small and large plots consisted of artificial defoliation at 25, 50, and 75 percent. Undefoliated trees were maintained as controls. Each treatment, along with controls, was replicated 3 times for a total of 12 small plots and 12 large plots.

We constructed a “defoliation device” that roughly mimics the pattern of defoliation inflicted on the tree by the CLB to artificially defoliate trees. The defoliation device consisted of a 4-foot PVC pole with three to four segments of rubber clothesline (10 to 16 inches in length) attached to the end. Tied to the ends of the segments were large treble hooks. When applied, the outer branches and leaves of the tree are struck with the hooks, causing leaf tissue to be torn and broken away.

Defoliation treatments were assigned randomly to plots. In order to assess defoliation levels, tree heights were measured. Assigned defoliation percent, based on that measured height, was determined from the top down, and the lower limit was marked with flagging. For example, the top 25 percent of a tree would be treated in the “25 percent

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

defoliation" category. Only leaf plastochron index (LPI) 1 to 8 was damaged. Defoliation treatments were applied in May and August 2000.

Tree Measurement and Data Analysis

Diameter and total height were recorded pre- and post-treatment. Height was measured with an extension pole. Diameter was measured at 1 foot above the ground because many trees were too short to measure at diameter at breast height. Diameter was measured with calipers, with two measurements taken to produce an average value for each tree. The effect of defoliation treatment on height and diameter for measured trees was assessed using analysis of variance (ANOVA) and Fisher's PLSD (SAS Institute 1998).

RESULTS

Artificial defoliation at all levels had a significant effect on height growth when compared to control trees ($F = 14.417$; d.f. = 3,410; $P = <0.0001$). On average, undefoliated control trees were significantly taller than defoliated trees. Trees defoliated at 50 and 75 percent exhibited the most decreases in growth (fig. 1). Height growth for trees defoliated at these levels was reduced by 30 and 31 percent, respectively. Trees defoliated at 25 percent were reduced in growth by 24 percent when compared to controls.

Whereas artificial defoliation appeared to have no significant effect on diameter growth ($F = 1.762$; d.f. = 3,102; $P = 0.1592$), defoliated trees did exhibit some reduction in diameter. Trees defoliated above 50 percent had the greatest growth loss (23-26 percent), but diameter growth for trees defoliated at 25 percent did not decrease (fig. 2).

For the 2000 growing season, most height gain occurred from May to August (fig. 3), with slower gains thereafter. This pattern was consistent for defoliated and control trees. Control trees gained approximately 5.3 feet in height. Trees defoliated at 25 percent gained 4.0 feet, whereas trees defoliated above 50 percent gained only 3.5 to 3.6 feet on average. Diameter growth increased steadily over 2000, with control trees gaining 0.77 inches. Trees defoliated at 25 percent gained 0.69 inches, whereas trees defoliated above 50 percent gained only 0.57 to 0.59 inches (fig. 4).

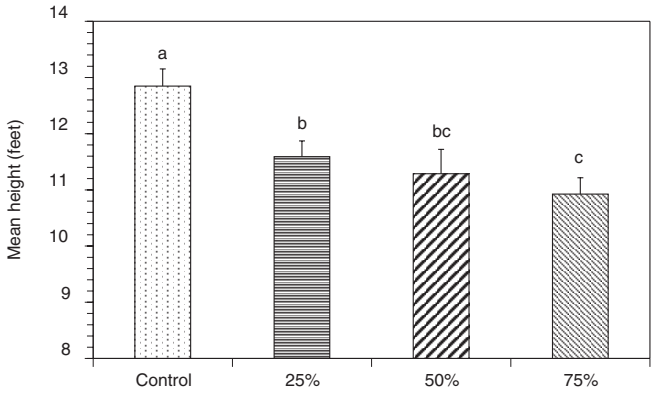

Figure 1—Mean height growth compared across artificially defoliated and control trees.

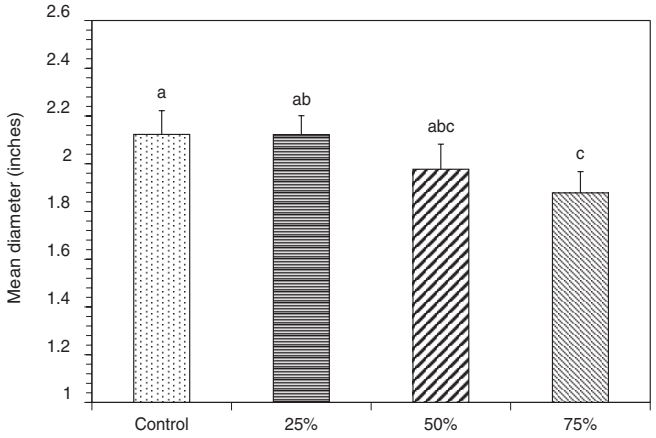

Figure 2—Mean diameter growth compared across artificially defoliated and control trees.

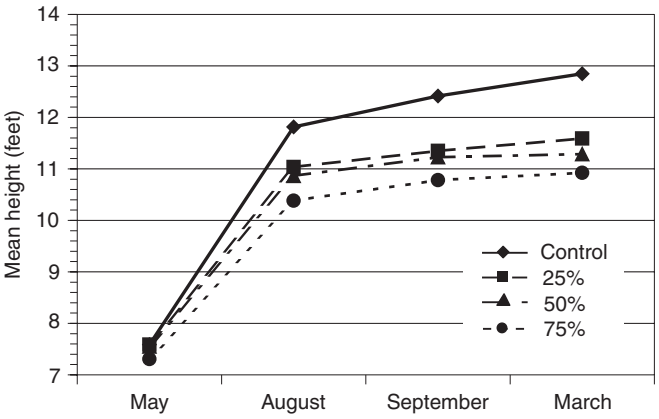

Figure 3—Mean height growth over time for artificially defoliated and control trees.

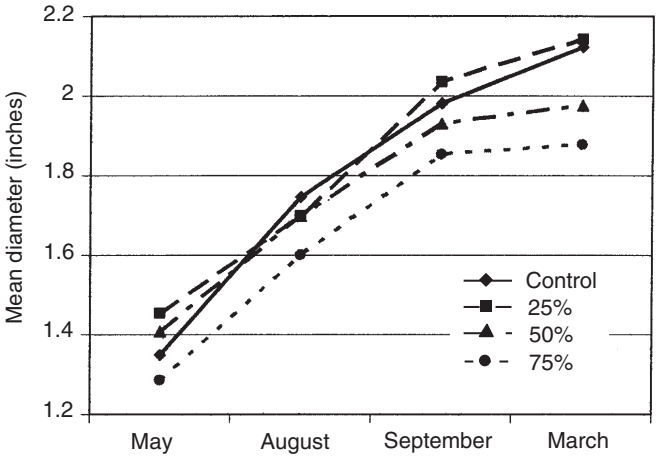

Figure 4—Mean diameter growth over time for artificially defoliated and control trees.

DISCUSSION

Our results indicate that increasing severity of defoliation can lead to correspondingly significant decreases in growth. This concurs with earlier studies examining the effects of artificial defoliation on *Populus* by Bassman and others (1982) and Reichenbacker and others (1996). In our study, the most pronounced reductions occurred for height. Defoliated trees, on average, lost 24 to 31 percent in height growth when compared to undefoliated trees. Reductions were noticeable across the entire range of defoliation treatments, from light to severe. No significant decreases in diameter growth were observed between defoliated and undefoliated trees.

Loss in height gain is, in part, attributable to damage inflicted to terminals during the process of artificial defoliation. Our defoliation technique was intended to mimic natural CLB defoliation. Although mechanically different, damaged terminals are a typical end result of CLB feeding activity, particularly during heavy infestations. Consequently, our results should reflect real impacts that could be anticipated from comparable levels of CLB defoliation.

Although based upon simulated defoliation, it appears that even relatively low level CLB defoliation (25 percent) could have a marked impact upon biomass accumulation in *Populus* plantations. However, what level of defoliation is tolerable will most likely be dictated by the economics of managing a CLB infestation. Some questions that need to be considered are: Is the potential reduction in growth loss so great that pesticide application is required? Is it economically feasible to leave the plantation alone? Based on these results, it would seem important for managers of *Populus* plantations to treat CLB infestations as soon as they are noticed early in the season.

ACKNOWLEDGMENTS

Funds for this project were provided in part through the Mississippi Agriculture and Forestry Experiment Station.

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LONGHORNED BEETLES IN GREENTREE RESERVOIRS AND NATURALLY FLOODED BOTTOMLAND HARDWOOD STANDS

Michael D. Warriner, T. Evan Nebeker, and Steven A. Tucker[1]

Abstract—Greentree reservoirs are bottomland hardwood forests that are artificially flooded during fall/winter to provide habitat and food for wintering waterfowl. Research has indicated that this practice could negatively impact bottomland hardwood stands leading to decreases in mast production, tree vigor and growth, and regeneration. Outside of waterfowl and aquatic macroinvertebrates, little research has been conducted regarding the effects this management practice has on other faunal elements. In this study, we examined longhorned beetle diversity and abundance in greentree reservoirs and naturally-flooded bottomland hardwood stands in Mississippi. Longhorned beetle species composition and levels of abundance were similar among greentree reservoir and naturally-flooded stands. Examination of species assemblages collected from greentree reservoirs did not reveal the presence of large numbers of longhorned beetles known to attack healthy and/or stressed trees. The largest number of species and individuals collected from all study sites were ones with associations with dead woody material.

INTRODUCTION

Greentree reservoirs are bottomland hardwood forests that have been impounded with levees and are temporarily flooded during fall and winter to provide food and habitat for wintering waterfowl (Rudolph and Hunter 1964). Research has suggested that this practice can negatively impact bottomland hardwood stands, leading to decreases in mast production (Francis 1983), tree vigor and growth (King 1995, Schlaegel 1984), and regeneration (Young and others 1995). There is also evidence that the artificial flooding regimes applied to greentree reservoirs can shift tree species composition towards more flood tolerant species (Karr and others 1990, King 1995). Problems associated with these sites can often be tied to inundation that extends into the growing season (Wigley and Filer 1989), reducing soil aeration, killing less water-tolerant tree species, and increasing overstory mortality (King and Allen 1996).

Although a body of knowledge exists regarding the impacts of greentree reservoir management on bottomland hardwood vegetation, little attention has been paid to faunal communities in these settings (King and Allen 1996). Faunal studies conducted thus far have generally been confined to waterfowl (Allen 1980, Arner and others 1974) and aquatic macroinvertebrate communities (Duffy and Labar 1994, Hubert and Krull 1973, Krull 1969, Wehrle and others 1995) with little attention paid to terrestrial animal taxa. What impact this management practice has on various terrestrial faunal groups should also be evaluated.

Though little studied in bottomland hardwood forests, insects have the potential to provide useful information regarding environmental changes (Kremen and others 1993). Insects are a fundamental component of forest ecosystems, performing important ecological roles from pollination, nutrient cycling, to predation (Packham and others 1992). Thus far, most insect-related studies conducted in southern forested wetlands have taken the form of faunal surveys (Allen and Thompson 1977, Goff 1952, Shelford 1954) or examined the influence of natural disturbances on insects and other terrestrial arthropods (Gorham and others 1996, Gorham and others 2002, Uetz and others 1979). Fewer still have investigated the impact of forest management practices on insects in these systems (Thompson and Allen 1993, Warriner and others 2002).

Longhorned beetles (Coleoptera: Cerambycidae) are an entirely phytophagous group of insects composed of species that feed on a range of woody and herbaceous plant species (Linsley 1959). While the adult stage of a number of species do not feed, the larvae of most all species bore within and feed upon plant tissues. Adult longhorned beetles are known to exhibit distinct preferences regarding oviposition sites, specifically as it relates to larval host condition (Hanks 1999). Oviposition preferences can often be very specific and can range from healthy and stressed trees and herbaceous plants to dead and decaying woody material (Yanega 1996). Although some longhorned beetles are recognized as important economic pests due to their wood-boring tendencies (Beal and others 1952, Donley and Acciavatti 1980, Galford 1916, Solomon 1980), most species feed on dead and decaying woody hosts (Yanega 1996), playing vital roles in the initial fragmentation and breakdown of dead wood in forest ecosystems (Harmon and others 1986).

Information regarding larval host preference is available for a large number of longhorned beetle species (Craighead 1923, Hanks 1999, Hanula 1996, Solomon 1995, Yanega 1996). Due to their close ties to both living trees and dead woody material, longhorned beetles could provide useful information about the forests in which they occur (Yanega 1996). Our objective in this study was to ascertain what

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

impact greentree reservoir management has on longhorned beetle diversity and abundance. In particular, we wanted to assess whether artificial flooding regimes influenced the representation of longhorned beetle species within certain larval host preference groups.

STUDY SITES

This study was conducted at Noxubee National Wildlife Refuge in east-central Mississippi during the summer of 2000. Approximately 5,300 ha of the refuge are comprised of bottomland hardwood forests (Duffy and LaBar 1994). Study sites consisted of two greentree reservoirs and two unimpounded bottomland hardwood stands. Greentree reservoirs were approximately 240 ha and 220 ha in size. Both greentree reservoirs had been artificially flooded on a nearly annual basis since the mid to late 1950's (Young and others 1995). The two sites were typically inundated, with water from a nearby lake, starting in late November or early December with drawdown by late February to early March (Wehrle and others 1995).

Two unimpounded bottomland hardwood stands, exposed to natural flood patterns, served as controls. The two stands were approximately 100 ha and 80 ha in size. Composition of dominant tree species within greentree reservoirs and naturally flooded study sites was relatively similar, although overcup oak (*Quercus lyrata* Walt.) was more common within the two greentree reservoir sites. Along with overcup oak, dominant tree species included water oak (*Q. nigra* L.), willow oak (*Q. phellos* L.), cherrybark oak (*Q. pagoda* Raf.), American sweetgum (*Liquidambar styraciflua* L.), and red maple (*Acer rubrum* L.).

METHODS

Insect Sampling Procedures

Longhorned beetles were sampled using Malaise traps and window traps. Malaise traps are large tent-like structures that passively trap low-flying insects and collect them in a container filled with a preservative/killing agent (Townes 1972). Samples of Malaise trapped beetles have been shown to be characteristic of recognizable communities and strongly related to habitat variables up to 50 m from traps (Hutcheson 1990; Hutcheson and Jones 1999). Collecting containers were filled with 70 percent ethanol. Two Malaise traps were placed in each greentree reservoir and naturally flooded stand. Traps within a single stand were at least 50 m from the nearest road and 150 m apart. Window traps (flight-intercept trap) were also deployed at each study site. Window traps, modified from Økland (1996), consisted of two perpendicular clear plastic sheets (35 cm x 40 cm) attached to a collecting container (33 cm diameter). Collecting containers were filled with propylene glycol. A roof was placed on top of the intersecting clear plastic sheets to prevent rainfall from flooding the collecting container. Window traps were hung between two trees at a height of 2 m. A total of six traps, spaced 20 m apart, were placed at each study site. All traps were operated continuously, from mid April to late October 2000. Traps were serviced, and collected insects removed every two to three weeks. Collected longhorned beetles were sorted, stored in 70-percent ethanol, and identified to species. Larval host preferences for collected species were determined from Craighead (1923), Hanks (1999), Hanula (1996), Solomon (1995), and Yanega (1996). Based upon those preferences, species were assigned to one of four host groups. Larval host groups, modified from Hanks (1999), were as follows:

1. healthy hosts-species feeding on healthy woody plants
2. weakened/stressed hosts–species feeding on woody plants weakened by disease, injuries, or other causes
3. dead/decaying hosts–species feeding on downed or standing dead trees and branches in various stages of decay
4. unknown hosts–species for which larval host preference is unknown.

Data Analysis

Similarities in longhorned beetle species composition among greentree reservoirs and naturally-flooded stands were assessed using the Morisita-Horn index (Wolda 1981). This index produces a value of one when two samples possess identical faunas and a value of zero for two samples with completely different faunas. The Morisita-Horn index is based upon abundance data, rather than binary data, and therefore performs more effectively than some qualitative indices (Magurran, 1988). The index is also less dependent upon sample size and diversity than other quantitative indices (Wolda 1981). Distribution of number of species and individuals (pooled data) belonging to specific larval host preference groups were compared between greentree reservoirs and naturally-flooded stands using a Chi-square test.

RESULTS AND DISCUSSION

A total of 829 longhorned beetles representing 49 species were collected from the greentree reservoirs. In the naturally-flooded stands, 930 individuals comprising 47 species were trapped. Faunal similarities among greentree reservoirs and naturally-flooded stands, as expressed by the Morisita-Horn index, were high (> 0.80) indicating few differences in species composition among the four individual study sites (table 1).

The majority of longhorned beetles trapped were species with oviposition preferences for woody plants (deciduous trees and shrubs). Within this wood-feeding group, the largest number of species and individuals were characterized by associations with dead woody material (table 2). Species feeding on weakened/stressed hosts made up a

Table 1—Comparison of longhorned Beetle faunas (Morisita-Horn) collected from greentree reservoir and naturally flooded bottomland hardwood forest study sites

	NFBH 2	GTR 1	GTR 2
NFBH 1	0.92	0.83	0.82
NFBH 2	0.84	0.82	
GTR 1			0.87

NFBH = naturally flooded bottomland hardwood; GTR = greentree reservoir.

Table 2—Number of longhorned beetle species and individuals by larval host preference in greentree reservoir and naturally flooded bottomland hardwood forest study sites

	GTR		NFBH	
Larval host preference	Species	Individuals	Species	Individuals
Healthy host	3	36	4	35
Weakened and stressed hosts	9	61	7	82
Dead and decaying hosts	30	623	28	716
Unknown hosts	7	109	9	96

GTR = greentree reservoir; NFBH = naturally flooded bottomland hardwood.

smaller portion of the species collected. Even fewer trapped beetles belonged to species known to feed only on healthy hosts. Numbers of species within each larval host preference group did not differ between greentree reservoirs and naturally flooded stands ($\chi^2 = 0.84$; df = 3; $P = 0.8399$). Numbers of individuals within each group also did not differ ($\chi^2 = 4.71$; df = 3; $P = 0.1943$).

As mentioned above, the most frequently collected longhorned beetles from both greentree reservoirs and naturally-flooded stands were those associated with dead wood. Of these, *Elaphidion mucronatum* (Say) (dead branches), *Curius dentatus* Newman (dead branches), *Neoclytus mucronatus* (Fabricius) (under bark of recently dead trees), *Orthosoma brunneum* (Forster) (well-decayed, moist wood), and *Strangalia luteicornis* (Fabricius) (well-decayed, moist wood) were the most abundant. Additional dead-wood feeding species included *Distenia undata* (Fabricius) (roots of recently dead trees), *Ecyrus dasycerus* (Say) (dry dead wood), *Saperda lateralis* Fabricius (moist dead wood at base of trees), and *Typocerus acuticauda* Casey (moist, decaying wood). Species with preferences for healthy hosts were collected in smaller numbers and consisted of a few twig-girdling species such as *Anelaphus villosus* (Fabricius), *Doraschema alternatum* (Say), *Goes debilis* LeConte, and *Obera praelonga* Casey as well as the root-feeding (oaks) *Prionus imbricornis* (Linnaeus). Longhorned beetles associated with weakened/stressed hosts included *Hyperplatys aspersa* (Say) and *N. acuminatus* (Fabricius). The remaining group of longhorned beetles included a number of species whose host plants have yet to be identified.

Based upon our limited data, greentree reservoir management did not appear to represent a suppressor to longhorned beetle diversity or abundance. Most of the longhorned beetle species collected from naturally-flooded stands were also present in the greentree reservoirs. Abundances of species shared between greentree reservoirs and naturally-flooded stands also did not differ greatly. In addition, representation among larval host preference groups did not differ, possibly indicating the availability of similar levels of host resources (dead wood, weakened trees) in both settings.

As a group, longhorned beetles are probably little affected by flooding that does not extend into the growing season. Flooding in bottomland hardwood forests typically occurs during the winter to early spring, a time when the larvae of most longhorned beetles are still within the woody confines of their hosts. However, if flooding extended well into the growing season when some species emerge from their hosts, mortality could occur, particularly in those species associated with downed wood on the forest floor.

Many of the problems associated with greentree reservoir management such as shifts in tree species composition, reduced mast production, and tree mortality often result when water is impounded into the growing season. It has been estimated that less than 20 percent of greentree reservoir managers remove impounded water by their target date (Wigley and Filer 1989). Managers at Noxubee National Wildlife Refuge generally remove water from their greentree reservoir by January to early February, well before spring. Greentree reservoirs managed less stringently than those examined by this study should be examined to determine whether flooding into the growing season impacts the longhorned beetle fauna within those forests.

ACKNOWLEDGMENTS

We would like to thank the staff of the Noxubee National Wildlife Refuge for their input into selection of study sites and access to refuge property. Terry Schieffer of the Entomological Museum at Mississippi State University provided invaluable assistance in species identification and verification. Funds for this project were provided in part through the Mississippi Agriculture and Forestry Experiment Station.

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Growth and Yield

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STAND DENSITY AND CANOPY GAPS

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Abstract—Estimation of stand density is based on a relationship between number of trees and their average diameter in fully stocked stands. Popular measures of density (Reineke's stand density index and basal area) assume that number of trees decreases as a power function of diameter. Actually, number of trees drops faster than predicted by the power function because the number depends, in addition to tree size (diameter), on the area of gaps between tree crowns. The gaps are inevitable even in dense even-aged stands with sizeable crown overlap. Taking both factors of self-thinning (increasing tree size and gap area) into account improves estimation of stand density and clarifies several other issues.

INTRODUCTION

Competition among trees is one of the main factors determining their growth and survival. This factor, unlike many others, can be easily and often profitable controlled by thinning. The problem is to find an optimal level of competition. To tell whether it is too low or too high, we need (1) a method to assess the current level of competition in a given stand and (2) some benchmark of competition which can be linked to its optimal level. Stand density is a good proxy of many complex processes involved in competition among trees in a given stand. Foresters have done much to devise various measures of density and establish benchmarks of this variable. Still, there is plenty of room for improvement. The key point is to account for canopy gaps resulting from self-thinning. Though not as popular as basal area, stand density index is a most promising measure of density. This report will examine its advantages and disadvantages, propose a new measure of density accounting for canopy gaps, and identify normal and complete density levels.

STAND DENSITY INDEX

Reineke (1933) developed his index of density assuming that the relationship between the number of trees per unit area of fully-stocked stands and their average diameter is linear (on the log-log scale):

$$\ln N = \ln a - r \ln \frac{D}{25.4} \qquad (1)$$

In this equation, *a* is the density of fully-stocked stands, also known as normal or equilibrium density. It is measured by number of trees with a specified diameter (25.4 cm). This level of density is achieved when mortality matches the expansion of crowns, so that crown closure is supposed to remain constant. Reineke realized the relevance of this relationship to estimating density and proposed the stand density index, *S*:

$$S = N\left(\frac{D}{25.4}\right)^r \qquad (2)$$

This definition applies to stands with any stocking; however, parameter *r* must be found in fully-stocked stands. Reineke considered this parameter to be a constant equal to 1.605 for all species and locations. The precision he reported is curious, particularly because Reineke obtained this estimate guided by intuition rather than calculation. When MacKinney and Chaiken (1935) reanalyzed the same data using standard statistical methods, they obtained the power of 1.7070. On permanent plots established in young (average age of 20 years) loblolly pine (*Pinus taeda* L.) stands, Williams (1994, 1996) found the power of 1.5. Using mostly temporal and older plots (from 19 to 77 years) of the same species in the same region (northern Louisiana), Meyer (1942) came up with the value of 1.9.

Biological Interpretation of Reineke's Constant

The form and parameters of equations that reflect mechanisms of growth can be discussed in terms of biology, in addition to statistics. Such equations are useful not only for data description but for our understanding as well. As far as equation (1) is concerned, it can be shown that Reineke's constant is a measure of intraspecific competitive ability of trees, called self-tolerance by analogy with tolerance (Zeide 1985). Tolerant species utilize light of lower intensity and other resources more fully than do intolerants, and their canopies are denser. Therefore, they survive better in mixed stands than do intolerants of the same crown class and age. Tolerance is the interspecific competitive ability of trees.

Albeit tolerance predicts the success in competition with other species, it tells little about the ability of trees to coexist with conspecifics. In pure stands, the capacity of tolerant species to withstand shade is counterbalanced by their denser canopies, just as higher light requirements of intolerant species are matched by their sparser canopies. Light utilization and canopy density work in opposition, precluding any inference about the relationship between tolerance and mortality in pure stands. For managing plantations, we need to know a species self-tolerance, that is the ability of trees to compete with or tolerate conspecifics. Self-tolerance, and not tolerance, is relevant for determining optimal planting density, thinning intensity, and other activities in pure stands.

A sensible measure of self-tolerance is the proportion of trees, *-dN/N*, eliminated by a certain increase in average diameter, *dD/D*:

$$Self - tolerance = \frac{-dN/N}{dD/D} \qquad (3)$$

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

The smaller the ratio, the fewer trees succumb with the same increase of diameter, and therefore, the more self-tolerant is the species. On the other hand, by differentiating Reineke's relationship [equation (1)], we obtain the following expression for *r*:

$$r = \frac{-dN / N}{dD / D} \quad (4)$$

The identity of (3) and (4) indicates that *r* is a measure of self-tolerance. Having this measure, we can compare ranking of tree species with respect to their self-tolerance and tolerance. For southern pines, the relationship is reversed: the least tolerant longleaf pine (*Pinus palustris* Mill.) was found to be the most self-tolerant, while the most tolerant slash pine (*P. elliottii* Engelm.), for which *r* is 25 percent greater, the least self-tolerant (Zeide 1985). This means that when average diameter in fully stocked stands of slash pine increases by 1 percent, they loose 25 percent more trees than do longleaf pine stands.

Doubts About Reineke's Index

Reineke's index is described in mensuration textbooks, sometimes used by researchers, but seldom by practicing foresters. The Forestry Handbook (Wenger 1984) mentions the index in passing and does not even define it. The acceptance of Reineke's index was hampered by the lack of biological interpretation and empirical faults. The "statistical basis" for the relationship advanced by Reineke is questionable and not altogether relevant; it is his belief that "stands of all ages on all sites have essentially the same characteristic frequency-curve form" (Reineke 1933). Many researchers noticed that number of trees drops faster than follows from the power function of diameter (Briegleb 1952; Meyer 1938, 1942; Spurr 1952; Zeide 1995). For this reason, Meyer (1938) used a curved-down (on the log scale) line. Wahlenberg's (1960) corrections of stand density index exhibit a similar downward trend.

A thorough, though not entirely consistent, examination of Reineke's index was done by Spurr (1952). While acknowledging that the correlation of stand density index with age is much lower than that of basal area, he still concluded that "since basal area is apparently fully as satisfactory as stand-density index in most cases, because it is simply obtained, and since it is a finite value in comparison to stand-density index which is an approximate value, it is to be preferred as a measure of density" (Spurr 1952).

Spurr's view was endorsed by the committee on stocking of the Society of American Foresters which, after 8 years of deliberation, found that Reineke's index changes with tree size and age and decided that the index "does not appear to be a good measure of density" (Bickford and others 1957). This tendency to dismiss what may be the most significant American contribution to forest science persists until present. The leading textbook of forest mensuration, published 50 years after Spurr's book, echoes his opinion and even his words: "in most cases BA [basal area] is fully as satisfactory as stand-density index, and because it is more simply obtained, it is preferred as a measure of density" (Avery and Burkhart 2002). It may be that Reineke's index is not a good measure of density, but it is the best we have. At least it does not lead to the confusion between overstocked and understocked stands of the same species as basal area does. However, the relationship between the number of trees and diameter may be not as simple as Reineke believed.

TWO CAUSES OF SELF-THINNING

Natural mortality (self-thinning) is caused by two factors: increase of tree size [represented by diameter in equation (1)] and decrease of tolerance, which leads to the accumulation of the area of gaps between tree crowns. To understand why gaps are inevitable, even in dense stands with a sizeable overlap of crowns, let us consider the dynamics of canopy closure.

Canopy Closure in Fully Stocked Stands

Canopy closure is a compromise between two opposing processes: lateral growth of crowns, which increases horizontal closure and mortality of trees, which diminishes it. The following arguments suggest that, after crown closure at about the time when height growth peaks, the second process predominates, and the area of gaps builds up with age and tree size: (1) As trees grow older and taller, they allocate an increasing proportion of their resources to support and maintain the crown. Unable to invest as much resource to adapt to deficiency of light as do younger trees, each year trees become less tolerant to shade; (2) with age, the size of a gap created by a fallen tree increases, while the ability of neighboring trees to close the gap decreases. Although the same factors (increased size of dying trees and decreased growth of their neighbors) reduce mortality, due to declining tolerance (and self-tolerance), canopy closure diminishes; (3) when other factors are equal, the ratio of average crown length to crown width increases with diminishing canopy closure. A sample across many forest stands shows that crown length increases faster than crown width (Zeide 1991); and (4) seed production increases with age and tree size, and it is of selective advantage for older trees not to choke their progeny but loosen the canopy and provide light for advance regeneration.

The first process of crown enlargement is not purely physical. Its effect is determined by the level of tolerance or, in pure stands, of self-tolerance of a species. The second process of gap accumulation results from the change of this level. Our understanding of density and stand dynamics in general will benefit from assessing each process (increasing average crown size and diminishing closure) separately.

Augmenting Reineke's Relationship

If number of trees is a function of two predictors instead of one, it is natural to add to equation (1) a module describing the diminishing crown closure. This module would unload the power of diameter (parameter *r*) from representing the change in closure, in addition to tree size. To construct such a module we need to select its form and a driving variable. The observations that the number of trees falls faster than the power function suggest the exponential form. Because tolerance decreases with increasing age and tree size, either of these variables can be used to drive the module of canopy closure. Thus, the relationship between number of trees and average diameter in fully stocked stands can be written as:

$$\ln N = \ln a - b \ln \frac{D}{25.4} - c(D - 25.4) \quad (5)$$

where *a* is normal stand density, *b* is the rate of tree mortality caused by the increase in crown size, and *c* is the mortality rate due to diminishing canopy closure. Accordingly, stand density index is:

$$S = N\left(\frac{D}{25.4}\right)^{b} e^{c(D-25.4)} \quad (6)$$

As does Reineke's index, equation (6) defines stand density as the number of trees per unit area with $D = 25.4$ cm (this is why 25.4 is subtracted from *D* in the closure module). This definition applies to any even-aged stand though, as with Reineke's parameter *r*, parameters *b* and *c* have to be found in fully stocked stands. The definition [equation (6)] does not impose canopy gaps. If canopy closure is complete, *c* would be 0 and equation (6) would be reduced to equation (2). Equation (5) explains why steeper slopes are observed in older stands with larger diameters [1.9 reported by Meyer (1942) as compared with 1.5 found in younger stands observed by Williams (1994, 1996)]. When number of trees is approximated by a power function of diameter [equation (1)], parameter *r* increases with diameter because it equals:

$$r = b + \frac{c(D-25.4)}{\ln\frac{D}{25.4}} \quad (7)$$

DATA

Equations (1) and (5) were fitted to the data from one of the oldest active thinning and pruning studies of loblolly pine located near Monticello in southeastern Arkansas. This study was established on 40 plots in a fully stocked ($S = 629$) 12-year-old plantation. Site index is 20 m (base 25 years). Five control plots were added at age 27. Reineke's slope for these control plots and 40 plot measurements before thinning was $r = 1.61 \pm 0.06$ ($R^2 = 0.95$, average number of trees per ha = 1,015). The height of even-digit upper stem diameters was measured by a Zeiss Teletop (lately by a Criterion 400). As a result, we have reliable estimates of total and merchantable volumes obtained using Grosenbaugh's height accumulation method. Tree diameters have been measured 11 times, the last time at age 43, which exceeds the rotation age for intensively managed loblolly pine plantations. A more detailed history of the study, description of methods, and the complete set of these data can be found on: http://www.afrc.uamont.edu/growthyield/montthinprun/index.html. The unmanaged plots of these data can be used to fit equation (5), though the small number of observations (70, of which 40 are at age 12) would make it difficult to obtain needed precision. A convincing way to check Reineke's parameter is to use his data. Such data were obtained by digitizing Reineke's (1933) Figure 7 B-E that depicts the number of trees and average diameter of fully stocked stands of southern pines. The stands were measured once and, as Reineke indicates, those with larger diameters may be on poorer sites.

RESULTS

The values of parameter *b* obtained by fitting equation (5), using SAS Proc Model, to the unmanaged plots of the Monticello study are 1.3-1.4 (table 1). However, the insufficient number of points (70) makes the error so large as to preclude any definite conclusion. The results from Reineke's data for southern pines are more certain (table 2) and allow one to conclude that: (1) Parameters *b's* are consistently lower than *r's*, which shows that gaps indeed increase with average diameter and, therefore, age; (2) as do Reineke's parameters, *b's* change with species and can serve as a measure of their self-tolerance; (3) both the Monticello and Reineke's data suggest that for loblolly pine $b = 1.35$; (4) similarity of these estimates (and those obtained by the growth approach below) justifies fixing this parameter to obtain more precise estimates of parameter *c* for the Monticello data (table 1); (5) the thinning rates of the canopy closure module (*c's*) are virtually identical for the studied southern pines and do not appear to be related to self-tolerance; and (6) the smaller value of *c* (0.0125) for the Monticello data may be a result of constant and relatively high site quality. It is likely that this parameter (but not *b*) is larger for poorer sites where usually canopy is less dense. This connection is supported by Reineke's data with its greater *c* (0.017) and by the site quality which decreases with stand diameter.

Table 1— Parameters of equation (5, log-transformed and untransformed) fitted to the unmanaged plots of the Monticello study

Predicted variable	*a*	*b*	*c*	R^2
lnN	619 ± 21	1.40 ± 0.55	0.011 ± 0.024	0.944
N	629 ± 23	1.31 ± 0.62	0.014 ± 0.029	0.948
lnNN	629 ± 15	1.31 ± 0.39	0.014 ± 0.018	0.945
				0.949
		Fixed b = 1.35		
lnN	621 ± 11	1.35	0.013 ± 0.002	0.945
N	629 ± 18	1.35	0.012 ± 0.003	0.949
lnNN	629 ± 9	1.35	0.012 ± 0.002	0.946
				0.950

R^2 = proportion of explained variance. Number of observations = 70

DISCUSSION

Quantifying Stand Characteristics

The proposed relationship between a number of trees and their diameter in fully stocked stands [equation (5)] clarifies self-thinning and leads to more precise definitions for several stand characteristics.

Maximum Density Index

Equation (5) accounts for the two self-thinning processes explicitly and allow us to reconstruct maximum index. Although in equation (5) *a* is the same as in (1), equation (5) contains another constant factor: *exp(*25.4*c)*. Actually, gap accumulation starts with $D = 0$ and not $D = 25.4$. Maximum stand density index, S_{max} is equal to the product of normal density index *a* and *exp(*25.4*c)*:

$$S_{\max} = ae^{25.4c} \quad (8)$$

This equation provides two density benchmarks: normal (with natural gaps) density, *a*, and complete (without gaps) density S_{max}.

Table 2—Comparison of parameters of equations (1) and (5) calculated using Reineke's (1933) data for southern pines.

Pine species	*N*	*r*	*a*	*b*	*c*
Loblolly	127	1.72 ± 0.04	729 ± 17	1.35 ± 0.21	0.017 ± 0.009
Longleaf	191	1.46 ± 0.04	649 ± 21	1.23 ± 0.19	0.015 ± 0.012
Shortleaf	179	1.98 ± 0.03	740 ± 12	1.71 ± 0.15	0.015 ± 0.008
Slash	121	1.87 ± 0.05	712 ± 18	1.58 ± 0.23	0.017 ± 0.013

N = number of temporary fully stocked plots.
Equation (5) explained 85-94 percent of variance, which was about 0.2 percent more than the proportion explained by equation (1).

Canopy Closure and Gap Proportion in Fully Stocked Stands

In normal stands described by equation (5) maximum density cannot be attained because it is diminished by the term *exp(-cD)*, which is the proportion of canopy closure. The complementary gap proportion is:

$$Gap\ \ proportion = 1 - e^{-cD} \tag{9}$$

For stands with D = 10 cm, it is 0.12 (if c = 0.0125), while for D = 40 cm the proportion is 0.39.

Maximum Stand Diameter

Decreasing self-tolerance and gap accumulation makes inevitable the decomposition of even-aged stands. Although stand decomposition is a continuous process, there is a moment when density of trees drops below a point where they stop competing with each other. Beyond this moment, the even-aged stand does not exist. What remains are lone trees that do not affect each other. Average diameter at this moment can be called maximum stand diameter. It is easy to detect this transition from separate trees to a stand, when density increases in young plantations with different spacing until trees start competing with each other and their diameter increment declines. This level of density has been documented in many spacing trials. For loblolly pine, it is equal to S_{min} = 135. This minimum level of stand density index was calculated using the above definition [equation (6)] with b = 1.35 and c = 0.0125] as the average of 11 paired indices (immediately before and after the onset of competition) from 4 different sources, including the pioneering Correlated Curve Trend study conducted in South Africa (Craib 1947).

Canopy closure [*exp(-cD)*] can be viewed as the ratio of the actual and maximum density indices. When the actual index $S = S_{min}$, the ratio equals:

$$\frac{S_{\min}}{S_{\max}} = \frac{135}{629e^{0.3175}} = e^{-cD_{\max}} \tag{10}$$

Hence, D_{max} = 149 cm.

Self-tolerance

Equations (3) and (4) identified r as a measure of self-tolerance. This neat result may be too simple. As does tolerance (Zeide 1985), self-tolerance is likely to decrease with age and tree size rather than stay constant. Having an improved relationship between a number of trees and diameter [equation (5)], we can differentiate it with respect to diameter and redefine self-tolerance as $b + cD$.

This measure can be improved by reversing it, so that high values correspond to high self-tolerance and by setting its minimum (absence of self-tolerance) to 0. This can be done by dividing the maximum value ($b + cD_{max}$) by the actual value and subtracting 1:

$$Self-tolerance = \frac{c(D_{\max} - D)}{b + cD} \tag{11}$$

In one number this measure captures three parameters of growth and survival.

Stand Density

Stand density is supposed to describe a degree of tree crowding. A dense stand means a well stocked stand, which makes the term "stocking" redundant. Density is a relative concept; it requires two quantities for its definition: one specific to a given forest stand and the other a standard common to all stands of a given species. Stand density index defined by equation (2) or (6) cannot express density because the standard varies among species. For example, Reineke (1933) found that for red fir (*Abies magnifica* A. Murr.) it is over two times larger than for loblolly pine. Therefore, the same density index means quite a different density for the fir and the pine stands. The advantage of Reineke's index is that this standard can be expressed by a single number rather than a vector of maximal basal areas. Although Reineke (1933) did not combine actual indices with species-specific standards into a single measure, he reported the extreme values for tree species he studied.

The density of stands with complete crown closure is a suitable density standard. Now when we know how to calculate it, stand density (not index), I, can be defined as the ratio of the index and maximum density:

$$I = \frac{S}{S_{\max}} = \frac{N}{a}\left(\frac{D}{25.4}\right)^{b} e^{c(D-50.8)} \tag{12}$$

For loblolly pine, normal density is $I = exp(-25.4c) = 0.73$.

Why b < 2?

Scarcity of growth resources represented by stand density depends largely on the area of the crown faces of neighboring trees intercepting the chief resource, light. In Euclidean geometry area has two dimensions, and the power of stem diameter that represents the crown area in the density index should be about 2. This would be the case if crowns were solid objects completely blocking or intercepting all the light. Then the effect of density would be substantially more detrimental to growth and survival than it actually is with b = 1.35. This number reflects the fact that crowns are

highly porous. They can be viewed as a collection of holes conducting sunlight and gases or as a multi-level hierarchy of clustered dots (pigment molecules and chloroplasts).

Euclidean geometry with its integral spatial dimensions does not work for many natural objects such as trees and their crowns. Crowns are fractals; they are hybrids of surface and volume with spatial dimensions [called by Mandelbrot (1983) "sponge dimensions"] between 2 and 3 (Zeide and Pfeifer 1991). The dimensions of their faces, named "sieve dimensions," vary from 1 to 2. Though not yet reported in literature for loblolly pine, they can be easily calculated using photographs. Sponge and sieve dimensions are related only by an inequality; their difference is less than one (Pfeifer and Avnir 1983). For loblolly pine crowns, sponge dimension was found to be 2.3 (Zeide 1998), which means that sieve dimension might be close to the constant component of self-tolerance, b = 1.35.

Stand Density Index and Basal Area

Basal area has a practical advantage over stand density index; it can be easily measured by point sampling. Foresters are familiar with this measure and use it widely to select trees for thinning. Therefore, it makes sense to express practical recommendations in terms of basal area. This can be done using these formulas:

$$BA = \frac{\pi 25.4^b e^{25.4c}}{40000} D^{2-b} e^{-cD} S = \frac{D^{0.65} S}{117.62 e^{0.0125D}} \quad (13)$$

and

$$S = \frac{40000}{\pi 25.4^b e^{25.4c}} D^{b-2} e^{cD} BA = 117.62 \frac{e^{0.0125D}}{D^{0.65}} BA \quad (14)$$

Application to Other Species, Sites, and Stands

Although the improved stand density index [equation (6)] is developed for loblolly pine, it may be applicable to other species, because the main thing about the equation that is species-specific is self-tolerance, which stands behind many model parameters. This characteristic, rather than botanical name or needle length, identifies loblolly pine in the developed models. They may help to manage other species as soon as their self-tolerance is known.

In this study, self-tolerance is shown to be a function of species and diameter. It is not clear whether self-tolerance also changes with site quality. Even though sparser canopies of stands on poorer sites transmit more light, the stands may be unable to utilize it to the same extent as do those on better sites. Here again the dual nature of self-tolerance leads to the question whether an increasing amount of available light balances its decreasing utilization. If so, self-tolerance would be site-invariant.

For uneven-aged and mixed stands, stand density index can be calculated as $\sum d_i^b \, exp(c \, d_i)$, where d_i is diameter of individual trees or average diameter of trees of the same species. The parameters of the index and growth equations have to be known for each species.

The presented model may be used to estimate damage caused by insects, diseases, and other disturbances. This damage often appears as canopy gaps. In the field, it is hard to separate these from the discussed gaps resulting from decreasing self-tolerance and get unbiased assessment of damage. The established dynamics of undisturbed canopy closure permit us to do this analytically. The improved definition of stand density, and specifically normal density [parameter a in equation (5)], is even a more convenient standard. It captures in a single number the state of forest stands regardless of their species, age, diameter, and site.

ACKNOWLEDGMENTS

I am grateful to many useful comments by Jayaraman Kadiroo, Ralph Meeker, and Mike Shelton. My thanks to Dan Leduc for digitizing Reineke's data. Support from the Arkansas Agricultural Experiment Station is appreciated.

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GROWTH AND DEVELOPMENT OF YELLOW-POPLAR PLANTATIONS ON THREE SITES RANGING FROM 9 TO 18 YEARS

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Abstract—Planting pine for conversion of former agricultural land to managed forests is well-documented, but little information is available for hardwood plantings. This study references three yellow-poplar (*Liriodendron tulipifera* L.) plantations (ages 9, 12, and 18 years) on different sites totaling 95 acres. The sites were located in middle Tennessee along a site productivity gradient composed of a floodplain and terrace site near the Cumberland River and an upland footslope site. All three sites had been in row crops or pasture prior to planting. Tree survival at time of measurement was greater than 75 percent for all three plantings. Average annual diameter increment and height increment for the three plantations were 0.5 inch and 4.2 feet, respectively. Comparisons of age, height, diameter, basal area, density, site index, and volume are made between the planted yellow-poplar in this study and three other published studies: natural stands of yellow-poplar and two studies with planted loblolly pine (*Pinus taeda* L.). Although site productivity and stand parameters differ among the studies, the growth of yellow-poplar plantations compares favorably with the natural stands of yellow-poplar and planted loblolly pine.

INTRODUCTION

Tennessee is 55 percent forested (14.4 million acres), and 89 percent of the composition is in hardwoods (Schweitzer 2000). The state has gained nearly 1.4 million acres of new forest land during the last 10 years, with about 600,000 acres reverting to other uses (May 1991, Schweitzer 2000). Through the Conservation Reserve Program, many acres of former agricultural land have been planted to pine. However, most nonindustrial forest landowners in Tennessee prefer to plant hardwood. The incentives for planting pine are poor. Tennessee has a lack of competitive markets for pine resulting in the lowest prices for pine pulpwood and sawtimber in the Southeast (Timber Mart-South 2002). Additionally, the recent southern pine beetle epidemic in Tennessee has killed nearly 400,000 acres of both natural and planted pine, about 33 percent of the total acreage categorized in pine types (Kauffman 2001).

Little information is available on afforestation of hardwoods on the better, more productive sites. Loblolly pine is not as site specific as yellow-poplar which typically occurs on the better sites, with a site index of 80 feet or greater at base age 50 years (Beck and Della-Bianca 1981). Yellow-poplar, with its fast growth and straight form, is a likely candidate for planting, especially on the better sites. The objectives of this study are two-fold: (1) to determine height, diameter and survival of three yellow-poplar plantations (planted in 1985, 1991, and 1994) on similar sites in Tennessee and (2) to compare growth of these plantations with natural yellow-poplar stands and planted loblolly pine as reported in the literature.

STUDY AREA

The study was conducted on three yellow-poplar plantations in Smith and Trousdale Counties in middle Tennessee at the transition between the Eastern Highland Rim and Nashville Basin Physiographic Regions. Braun (1950) described the vegetation of this area as part of the Western Mesophytic Forest, a transition area between the mixed Mesophytic Forest Region of the mountains to the east and the Oak-Hickory Region to the west. The three sites are within 10 miles of each other. Characteristics of each plantation site are as follows:

Site 1 is on a terrace of the Cumberland River. Soils are Ultic Hapludalphs (Armour series) formed in old alluvium overlying or in residuum derived from limestone (USDA-NRCS 2002). It was planted in 1991 and consisted of 32 acres. Site 2 is on the floodplain of the Cumberland River. Soils are Cumulic Hapludolls (Arrington series) formed in silty alluvium on floodplains and along drainageways (USDA-NRCS 2002). It was planted in 1994 and consisted of 25 acres. Site 3 is on the well-drained, footslopes. Soils are Typic Paleudults (Dellrose series), typically deep and well drained, formed in cherty colluvium (USDA-NRCS 2002). It was planted in 1985 and consisted of 39 acres.

Annual precipitation is 51 inches, usually evenly distributed in all seasons. Average site index (base age 50) is from 80 feet for upland oaks to 100 feet for yellow-poplar (Smalley 1983). All three study sites were former agricultural fields that were either row-cropped or in pasture. Each area was site prepared during the fall for planting the following year. Sites were cross-directionally disked followed by subsoiling in one direction. Each site was hand-planted at a 10 by 10-foot spacing using 1-0 yellow-poplar seedlings produced at the Tennessee Department of Agriculture, Division of Forestry nursery. The study sites, though planted at different times (years), were supervised by the same forester using the same procedures.

The only competition control used on these plantations after planting was mowing once or twice a year for the first 2 or 3 years. No herbicide was used during site preparation or following planting.

METHODS

Each plantation was sampled during the fall of 2002. Three 0.1-acre rectangular plots were randomly located in each plantation. Although a larger sample size might be desirable

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

with the size of these plantations, each plantation was fairly homogenous with little tree variation. Thus, larger sample sizes were deemed unnecessary. Diameter at 4.5 feet diameter at breast height (d.b.h.) was measured for each tree in the plot. Total height was recorded from a subsample of three dominant or codominant stems. Empty cells (missing trees) in each plot were recorded to determine survival percentages.

Data from this study on planted yellow-poplar stands is compared to three other studies: natural yellow-poplar stands (Beck and Della-Bianca 1970, 1981), loblolly pine plantations on abandoned fields in Tennessee, Alabama and Georgia (Smalley and Bailey 1974, Smalley and Bower 1968), and loblolly pine plantations on cutover sites in the West Gulf Coastal Plain (Feduccia and others 1979).

RESULTS

Growth and stand parameters of each of the three yellow-poplar plantations through the 2002 growing season are shown in table 1. Average annual diameter growth rate of all sampled trees ranged from 0.45 to 0.63 inch per year across the three sites. Average annual height growth rate of dominant trees ranged from 4.0 to 4.4 feet per year. If height growth continues at this rate, site index for yellow-poplar is estimated to be 115 to 120 feet at 50 years (Beck 1962), much greater than that estimated by the soil survey reports (USDA-NRCS 2002) and by Smalley's (1983) land-type classification system. Although Beck's yellow-poplar site index curves were formulated for the Southern Appalachian Mountains, they are the best available for the Eastern Highland Rim of Tennessee.

Table 1—Growth and stand parameters of three yellow-poplar plantations after the 2002-growing season in Smith and Trousdale Counties in Middle Tennessee

	Site 1	Site 2	Site 3
Growing season (yrs)	12	9	18
Mean dominant height (feet)	53	40	73
Mean diameter (inches)	7.6	5.3	8.5
Survival (percent)	76	87	78
Largest diameter tree (inches)	11.4	6.7	11.6
Basal area (ft2 per acre)	101	56	128
Number of measured trees (n)	96	110	98

Tree survival decreased as age of the stand increased (table 1). As trees became larger, the amount of available growing space became more limited causing mortality of lesser stems. Basal area per acre also increased with age.

Table 2 shows the stand, growth and yield parameters of the planted yellow-poplar at age 18 for site 3, natural yellow-poplar stands at age 20, and two growth and yield studies for planted loblolly pine at age 20. The planted yellow-poplar in this study had greater average diameters and dominant heights than the two loblolly pine studies and the natural yellow-poplar stands. The basal areas and volumes per acre fluctuated between studies presumably because of the number of trees per acre originally planted and the number of trees currently present. Site productivity (as measured in volume) in this study is similar to those in the other studies even though as measured by site index, the numerical value between species (yellow-poplar and loblolly pine) is expected to differ.

DISCUSSION

Each of these studies is based on different assumptions and parameters that make direct comparison of growth and yield difficult. The work of Feduccia and others (1979) was based on cutover sites without intensive site preparation before planting. The assumption was that intensively managed loblolly pine plantations, where pine density is carefully controlled throughout the rotation and utilization is more complete at final harvest, would need minimal site preparation for repeated crops of pine. The West Gulf Coastal Plain also has much different soils and geology than middle Tennessee.

Pine plantations measured to predict growth and yield in the Highland regions of Tennessee, Alabama, and Georgia

Table 2—Stand, growth and yield comparisons of planted yellow-poplar, natural yellow-poplar stands and two planted loblolly pine studies

	Planted YPP[a]	Natural YPP[b]	Loblolly pine[c]	Loblolly pine[d]
Age (years)	18	20	20	20
Mean height-overstory (feet)	73	66	61	53
Mean diameter (inches)	8.5	8.2	7.8	8.2
Basal area (ft^2 per acre)	128	112	144	112
Density (trees per acre)	325	310	436	303
Site index at 50 years (feet)	120 YPP	115 YPP	105 LP	105 LP
Average volume (ft^3 per acre)	3,116	2,939	3,625	2,920

YPP = yellow poplar.

[a] Eastern Highland Rim of TN (site 3 of this study) planted at 435 trees per acre.

[b] Southern Appalachian Mountains (Beck and Della-Bianca 1970).

[c] Abandoned fields of Highland areas in TN, AL and GA planted at 500 trees per acre (Smalley and Bowers 1968, Smalley and Bailey 1974).

[d] Cutover sites in the Gulf Coastal Plain planted at 400 trees per acre (Feduccia and others 1979).

(Smalley and Bailey 1974, Smalley and Bower 1968) were based on plantations established on agricultural fields with little evidence of damage from snow, ice, insects and disease; where stands have not been burned, thinned, or pruned; and where survival and tree distribution were judged reasonably good and no reinforcement planting had occurred. One would expect some degree of site preparation was used to establish loblolly pine on old-fields or pastures before planting. However, there is no mention in the text of site preparation or even if site preparation was considered in the selection of sample plantation sites. The sites in this study, although more upland, were more similar to the soils and geology found in middle Tennessee.

The natural yellow-poplar stands (Beck and Della-Bianca 1970) are from the mountains and coves of western North Carolina and north Georgia. Geology and soils are different from that of the study site in middle Tennessee. However, the differences between the planted stand and the natural stand are probably based on the patchiness that occurs with stems in natural stands and the more structured spacing in planted stands. Beck and Della-Bianca also chose to base their growth and yield predictions on the largest 25 yellow-poplar trees per acre in unthinned second-growth Southern Appalachian stands. These trees would be 3 to 5 inches larger than the average dominant at comparable ages (Beck and Della-Bianca 1970).

In this study, the fields were disked twice in perpendicular directions and subsoiled before planting. Disking and subsoiling are common practices to break plowpans or fragipans and soil compaction in old fields. This more intensive site preparation may have attributed to better growth and survival of planted seedlings when compared to the other studies. The fields were mowed once or twice a year for 2 or 3 years to control competition from grass and other broadleaf vegetation. Although mowing reduces the height of competing vegetation, the roots are still present, affecting the moisture uptake of planted seedlings. Most pine planting today uses a herbicide release to aid the early growth of pine seedlings. A herbicide release probably would have assisted the growth of planted yellow-poplar in this study.

SUMMARY

Although this study comparing growth, yield, and stand parameters of planted yellow-poplar to natural yellow-poplar and planted loblolly pine are not directly comparable because of the different site conditions, stand parameters, and assumptions made in collecting information for each study, it appears that the growth and yield of yellow-poplar and loblolly pine are similar. With height growth rates of greater than 4 feet per year and diameter growth rates of 0.5 inch per year after 18 years, yellow-poplar can achieve growth rates comparable to, if not greater than, loblolly pine especially on the more productive sites. Thus, hardwood planting of yellow-poplar is practicable on the studied areas as an alternative to pine planting. Site productivity for yellow-poplar is greater than hypothesized by the soil survey estimations (USDA-NRCS 2002) and Smalley's (1983) site classification system in the first 20 years after planting.

ACKNOWLEDGMENTS

Appreciation is expressed to Jim Replogle, forester with the Tennessee Department of Agriculture, Division of Forestry in Carthage, TN for access to and maintenance of the study areas. The author thanks Daniel Cassidy, Matt Olson, and Chris Oswalt for their assistance with data collection.

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PREDICTING AND PROJECTING STAND DOMINANT HEIGHT FROM INVENTORY DATA FOR YOUNG LONGLEAF PINE PLANTATIONS IN SOUTHWEST GEORGIA

John R. Brooks[1]

Abstract—A stand dominant height prediction technique, based solely on diameter distribution and total height data from standard inventory procedures, was investigated. The data consist of 15 managed longleaf pine (*Pinus palustris Mill.*) plantations that are part of a growth and yield study located in Worth, Mitchell, and Baker counties in southwest Georgia. A dominant height projection equation was also developed incorporating the results of this technique.

INTRODUCTION

In an effort to develop a dominant height projection equation as part of a growth and yield system for young longleaf pine (*Pinus palustris* Mill.) plantations, a practical method of estimating stand average dominant height from inventory data was investigated. A technique that utilizes standard inventory data has been successfully applied to site-prepared slash (Bailey and Brooks 1994) and loblolly pine (Bailey and Martin 1996) plantations. This technique was investigated for use with longleaf pine plantations in southwest Georgia that possess a wide range of initial planting densities, existing basal area per acre, and a limited range of stand ages.

STUDY DESCRIPTION

The longleaf pine data are part of a growth and yield study from 15 stands located in Worth, Mitchell, and Baker counties in southwest Georgia. Sample plots are approximately 0.1 acre (mean 0.10585) in size with stands ranging from 3 to 17 years old. Stand density ranges from 273 to 877 trees per acre and from 5 to 123 square feet of basal area per acre. Rectangular fixed area plots were established at different dates and have been remeasured annually; thus, the number of measurements available per plot ranges from two to seven. A total of 56 plot-measurement and remeasurement observations is available, providing 35 unique growth intervals.

At each measurement date, diameter at breast height (d.b.h.) was measured with a diameter tape and recorded for every tree to the nearest 0.1 inch. Total tree height was measured with a height pole or an Impulse 200 laser (depending upon tree size) and recorded to the nearest 0.1 foot. Trees less than 15 feet were measured with the height pole, whereas taller trees were measured with the laser. Initially, crown class was recorded for just the older stands (> 12 years) except for the most recent measurement period, where crown class was assigned to all trees, regardless of age. The traditional definition of crown class was slightly modified in order to assign crown class to the younger stands. The younger plantations generally have wider initial planting spacing, and, thus, all trees receive full sunlight. The codominant crown class was defined as those trees that make up the main crown canopy, whereas intermediate and suppressed classes were assigned to those trees visually shorter (and usually less vigorous) than the trees that constitute the average crown height.

PREDICTING AVERAGE DOMINANT HEIGHT

Bailey and Brooks (1994) reported that the average dominant height of a stand could be accurately estimated from a specified portion of a tree list sorted in descending diameter order without regard to crown class. Trees of the same d.b.h. measurement were also sorted in descending total height order. Starting with the largest diameter tree on the plot, smaller trees were consecutively included until the average tree height was equivalent to the measured average dominant height for the plot. It was found that the proportion of the diameter distribution that equated to the measured dominant height was quite stable. For planted slash and loblolly pine, this proportion was estimated to be 56.5 (Bailey and Brooks 1994) and 63.27 percent (Bailey and Martin 1996), respectively. This procedure was applied to all planted longleaf pine plot measurements that included a crown-class assignment. It was found that the average height of all trees in the upper 78.68 percent of the diameter distribution could be used as an estimate of dominant height, and that this proportion of the diameter distribution was quite stable, having a variance of 0.0045 square feet (table 1). The variance of this percentile was similar to that found in slash pine plantations (Bailey and Brooks 1994). The use of this average percentile to predict average domi-

Table 1—Descriptive statistics for the percentile of the diameter distribution that equates to average dominant height and the residuals and squared residuals based on the mean percentile (0.7868)

Statistic	PCT	($\hat{DHT}$-DHT)	($\hat{DHT}$-DHT)^2
n	33	33	33
Min	0.6338	-0.8880	0.0001
Max	0.9444	0.5415	0.7886
Sum		-1.1242	3.8991
Mean	0.7868	-0.0341	0.1182
Var	0.0045	0.1206	0.0267
RMSE			0.3438

$\hat{DHT}$ = predicted dominant height; DHT = measured dominant height.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

nant height resulted in a small negative bias (-1.124 feet), an average error of –0.03 foot, and a RMSE of 0.34 foot. The maximum residual in this dataset was only –0.88 foot (table 1). Of the predicted dominant height residuals, 79 percent were less than ± 0.5 foot, 97 percent were less than ± 0.75 foot, and 100 percent were less than 1.0 foot.

DOMINANT HEIGHT PROJECTION

A method of projecting dominant height as part of a growth and yield system was desired for all stand ages represented in this dataset. However, for most of the younger stands, only one remeasurement for each stand included the direct assignment of crown class. For those remeasurements where crown class was not measured, the preceding technique was used to estimate dominant height to provide additional growth intervals with which to fit the projection equation. Of the total plot measurements, 18 did not include a crown-class assignment. These were primarily the younger stands that were less than 10 years old. Average dominant height was predicted for these plots using the average height of the upper 78.68 percent of the diameter distribution. The fact that all residuals were less than 1 foot was felt to be an acceptably precise estimate. The algebraic difference equation form of the Chapman-Richards height/age projection function was selected as the model form:

$$DHT_2 = DHT_1 \left[\frac{1 - Exp\left(\beta_1 * A_2\right)}{1 - Exp\left(\beta_1 * A_1\right)} \right]^{\beta_2} \quad (1)$$

where:

DHT_2 = projected dominant height at age A2,
DHT_1 = current dominant height at age A1,
β_1, β_2 = parameters to be estimated from the data.

This equation form has been used successfully in both loblolly (Pienaar and Shiver 1980) and slash (Pienaar and Shiver 1984) pine plantations. All possible non-overlapping growth intervals were used to fit this nonlinear, two-parameter model. The results of the nonlinear fitting procedure are shown in table 2. Residual analysis indicated no unusual trends in the data when reviewed by stand age, dominant height, basal area, or trees per acre. The sum of the residuals indicates a slight negative bias (-0.3415) and a RMSE of less than 1 foot (table 3).

Table 2—Fit statistics and parameter estimates for the planted longleaf pine dominant height projection equation

		Asymptotic 95 percent confidence interval	
Parameter	Estimate	LCL	UCL
β_1	-0.085386	-0.111701	-0.059071
β_2	2.146169	1.795929	2.496408

MSE = 0.4123; RMSE = 0.6421 foot; R^2 = 0.996; n = 35.

Table 3—Descriptive statistics for the residuals and squared residuals based on the proposed stand dominant height projection model

Statistic	$(\hat{DHT}–DHT)$	$(\hat{DHT}–DHT)^2$
n	35	35
Min	-1.4828	0.0007
Max	1.0731	2.1986
Sum	-0.3415	13.6054
Mean	-0.0098	0.3887

$\hat{DHT}$ = predicted dominant height; DHT = measured dominant height.

rate estimate of stand average dominant height for the age classes and stand conditions examined. Nearly all residuals were less than 1 foot with an average residual of –0.034 foot and a variance of 0.0045 square feet. It is interesting to note that the diameter distribution percentile is much larger than that found for planted slash (56.5 percent) or loblolly pine (63.27 percent). Because the oldest age class in this data set is only 17 years old, a possible explanation would be that longleaf pine may not differentiate crown class as early as loblolly or slash pine.

A dominant height projection equation was fitted to 33 unique growth intervals consisting of 51 plot-age combinations. A portion of the youngest remeasurement data did not contain a crown-class assignment. In these instances, average dominant height was predicted using the upper 78.68 percent of the diameter distribution. All the data were then employed to fit a dominant height projection equation. Residual analysis did not indicate any unusual trends by measurement age, trees per acre, or basal area per acre. The RMSE for the projection equation was 0.62 foot with an average residual of –0.001 foot. It should be noted that any variance statement may be underestimated due to fitting the model with predicted data.

The technique employed provides an accurate dominant height prediction and projection system for the longleaf pine plantations that comprise this dataset. Due to the limited size of the dataset, no independent verification of this prediction system was tested. In addition, the effects of potential correlation from the use of plot remeasurement data have not been investigated. This dataset does include a variety of densities and includes cutover as well as oldfield sites. Extrapolation to other datasets should be conducted with caution due to the limited age distribution. However, it does provide a system that should be applicable to plantations in this region whose ages are consistent with those currently in the Conservation Reserve Program.

RESULTS AND CONCLUSIONS

This study indicated that the average height of the largest 78.68 percent of the diameter distribution provides an accu-

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REPRODUCIBILITY AND RELIABILITY: HOW TO DEFINE THE POPULATION OF TREES THAT REPRESENT SITE QUALITY FOR LONGLEAF PINE PLANTATIONS

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Abstract—We compared 13 definitions for the subpopulation of "site trees." Each subpopulation was defined (1) once at base age or at each measurement; (2) by crown class, diameter, or height; and (3) by the number of trees per acre. These subpopulations were applied to base ages of 25 and 50. For base age 25, the subpopulations defined at base age were superior to those defined at each measurement. The subpopulations defined by dominant and codominant trees were slightly superior to the subpopulations defined by the 40 tallest or thickest trees per acre. Generally, subpopulations defined by diameter were superior to subpopulations defined by height, and the subpopulations that included more trees were superior to those that included fewer. For base age 50, there was very little or no benefit from defining the subpopulations at base age. Among the subpopulations defined at each measurement, the one defined as dominant and codominant trees was superior. We selected this subpopulation for our site index modeling work. The results are largely explained by the stability of tree rankings within a plot over time. Ranking with respect to height is much less stable than ranking by diameter. Crown class was unexpectedly stable from measurement to measurement.

INTRODUCTION

Site index may be broadly defined as the average height of an arbitrarily defined subpopulation of trees in a stand at some arbitrarily determined base age. Site index is the most-used method to distinguish potential productivity of even-aged forests in North America (Carmean 1975, Goelz and Burk 1992). Site index is intrinsically a stand- or plot-level variable (Sharma and others 2002), but it is obtained from measurements of individual trees (Zeide and Zakrzewski 1993). Base age is generally selected so that it is slightly less than the expected rotation age for the species and region (Goelz and Burk 1996); in North America, it is typically between 25 and 50 years, although it may be less for short-rotation species.

One must choose what criterion to use to define the subpopulation of trees that indicate site quality. Various criteria specify the select subpopulation. Generally, regardless of the selection criteria for the subpopulation, damaged or defective trees are excluded, as such trees do not directly indicate site. The selection criteria are typically defined by crown class (Avery and Burkhart 1994), rank in diameter, or rank in height. When crown class is used, either the average height of dominants, or the average height of dominant and codominant trees combined, indicates site quality. When diameter or height is the criterion, either a fixed number of trees per unit of land or fixed proportion of trees on a plot define the subpopulation of trees that represents site quality. "Top height" is another term for the average height of the subpopulation of site trees (Zeide and Zakrzewski 1993). Zeide and Zakrzewski (1993) offered an alternative to using a single definition for the site tree subpopulation. Rather than using either a fixed number of trees per acre or a fixed proportion of trees per plot, they suggested a combined estimator that consisted of the "average of averages" of a fixed number and a fixed proportion of trees. For their data, this average of the averages cancelled out the biases of the two averages. In this way, it is roughly analogous to an antithetic variate type of estimator.

Site index models may be produced out of a more general growth-and-yield modeling effort, or they may arise out of a site evaluation context. The data for these two contexts tend to differ. In a growth-and-yield context, height-development data arise from remeasured permanent sample plots. Height may be measured on all or some subset of trees on these plots; diameter is typically measured on all trees. In a site evaluation context, height-development data often arise from stem analysis (Duff and Nolan 1953) of selected sample trees. Although the trees may all be within a fixed sample area, other nonharvested trees may not be measured for diameter or height. The term "top height" is more often applied to the growth-and-yield context than the site evaluation context.

It is simple to create a definition for the subpopulation of site trees and to determine the average height of those trees on a given plot. However, the trees that comprise that subpopulation change over time. As individual trees grow at different rates, a tree that was one of the 40 thickest trees at one measurement may not be in that class at some later measurement (Tiarks and others 1998). Given data from permanent sample plots, or even from stem analysis, it is possible to know or infer whether a tree belonged to the defined subpopulation at other ages. As this type of data is used to estimate site index equations, a model can specify membership in the subpopulation at base age, or can specify membership at each measurement. This is a critical decision: whether the trees in the subpopulation of interest should be defined at one time or redefined at each

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

measurement. In the first case, we only consider the trees in the subpopulation at base age. In the second case, different trees represent the subpopulation at each age, and, thus, the average height includes different trees from measurement to measurement. Presumably, the first case produces models with smaller variance when fit to data, as one source of variation is removed. However, using only base age might be a false economy; the fit to our data might be improved at the cost of relevance in application. In a site evaluation application, a user cannot be certain which trees were in the defined subpopulation at base age, given measurements at some other age.

So, the choice is between smaller errors in estimation or smaller errors (or objectivity) in application, or between reliability (small error) and reproducibility. Reliability suggests estimates that are more indicative of site quality. Reproducibility suggests greater objectivity, no need to guess which trees will be members of the subpopulation at any other time. In this paper we explore the issue of reliability (smaller error), discuss the processes that contribute to reliability, and incorporate the concept of reproducibility to guide decisions for a definition of site trees for a specific longleaf pine dataset.

MATERIAL AND METHODS

Data

The data arise from seven studies in the Gulf Coast States to investigate the effects of spacing and thinning on growth and development of longleaf pine plantations (Goelz and Leduc 2001). The 267 plots have been remeasured multiple times at approximately 5-year intervals; most plots have been remeasured for > 20 years. Some of the stands are now > 60 years old. The protocol varied among the studies. Most recent measurements include height of all trees, and a subset of heights was measured during earlier inventories of some of the studies. The studies have been combined to form a uniformly measured database for growth-and-yield modeling of longleaf plantations (Goelz and Leduc 2002).

Procedures

We compared 13 definitions for the subpopulation of site trees: (1) dominant or codominant crown class at time of measurement, (2) always dominant or codominant crown class before base age, (3) 40 tallest trees per acre at time of measurement, (4) 40 tallest trees per acre at base age, (5) 20 tallest trees per acre at time of measurement, (6) 20 tallest trees per acre at base age, (7) 40 thickest trees per acre at time of measurement, (8) 40 thickest trees per acre at base age, (9) 20 thickest trees per acre at time of measurement, (10) 20 thickest trees per acre at base age, (11) all trees within 10 percent of maximum height at time of measurement, (12) all trees within 10 percent of maximum height at base age, and (13) dominant or codominant crown class among 40 thickest trees per acre at time of measurement.

Definitions 1 and 2 include trees defined as open grown. More accurately, definition 2 trees were never anything other than dominant, codominant, or open grown; a missing observation of crown class at some age did not exclude trees from definitions 1 or 2. The following model represented our data well:

$$H = \frac{\alpha}{\left(1+\gamma A^{-\delta}\right)}, \quad (1)$$

where

H = height
A = age
α and δ = parameters common to all trees
γ = a parameter unique for each tree.

This model is equivalent to the equation of McDill and Amateis (1992) or, after rearranging terms, the Hossfeld IV equation (Zeide 1993). The estimate for parameter α, the asymptote, was 113.8217, and the estimate for δ was 1.49203. By solving for γ, then setting A equal to A_b, the base age (either 25 or 50), setting H equal to site index (S) and substituting back into equation 1, then solving for S, we get an equation to predict height at base age for individual trees, given an observation of height at a known age:

$$S = \frac{\alpha}{\left(1+\left(\frac{\alpha}{H}-1\right)\left(\frac{A_b}{A}\right)^{-\delta}\right)} \quad (2)$$

We used equation 2 to predict height at base ages of 25 and 50, given each observation of height and age. Then, using 13 subpopulation definitions, we calculated predicted S as the average predicted height of the appropriate trees. For the "true" value of S, we used the subpopulation definitions to calculate the average height measured at the appropriate base age. For some studies, heights were not measured at age 25 or 50, but at nearby ages. When there was a height measurement between 20 and 30 (for base age 25) or between 40 and 60 (for base age 50), we estimated the "true" value by nonlinear interpolation, employing equation 2.

We calculated error criteria to assess the variability of the estimates of S for the different subpopulation definitions and the two base ages. We calculated average error (-bias), mean squared error, mean absolute error, and maximum error. For some plots at some measurements (plot-by-measurement combinations comprise an observation), there were few or no trees that qualified for some of the definitions. In some of the studies, few heights were measured during the first few measurement cycles, and there were few surviving trees on some of the older plots. When fewer than two trees fulfilled the definition, the observation was deleted. When different subpopulation definitions produced different numbers of observations, Simpson's Paradox could provide misleading results. We sought to lessen this effect by deleting all observations for all subpopulations if the observations were not present for particular promising subpopulations. For example, we considered subpopulations 1 and 7 to be promising, so we recalculated the error criteria excluding the observations that were missing for those subpopulations, even though another subpopulation had an observation.

We suspected that the stability of ranks for individual trees would largely determine the variability for the

subpopulations defined by diameter and height. As well, the stability of crown class would largely determine the variability of the subpopulations defined by crown class. If these values fluctuated greatly from measurement to measurement, variability would be high. Thus we explored this source of variability by creating cross-classified tables to assess whether the change in the cumulative rank percentiles differed more for diameter or for height. We used the likelihood-ratio test (Fienberg 1980), G^2, with an of 0.05, to test whether rank percentile changed more for diameter or height; we also tested whether dominants and codominants or intermediate and suppressed trees switched to the alternate, broad crown class more often. These tests help explain stand dynamics in these longleaf pine plantations.

RESULTS AND DISCUSSION

Error criteria are provided in table 1. For base age 25, bias was very small for all subpopulations defined at base age. Mean absolute error and mean squared error were also lower for the subpopulations defined at base age than the counterpart subpopulations defined at each measurement. Among the subpopulations defined at base age, the subpopulation defined as dominant and codominant trees was lowest for all error criteria. The subpopulations defined by the 40 tallest and 40 thickest trees per acre were only slightly worse than the dominant and codominant subpopulation. Among the subpopulations defined at each measurement, the subpopulation defined by dominant and codominant trees had the lowest absolute and squared error, with the subpopulation defined by the 40 thickest trees having a slightly greater absolute and squared error, but a lower bias. Regardless of whether the subpopulations were defined at base age or at each measurement, and whether the subpopulations were defined by height or diameter, errors were lower when more trees were included in the subpopulation.

Table 1—Error criteria for site index predictions using 13 different subpopulations and 2 base ages (25 and 50)

Subpopulation	Observations	-bias	Mean error		Maximum difference
			Absolute	Squared	
	no.				
		Base age 25			
1. DC	958	0.388	2.664	13.173	15.885
2. DC -BA	672	0.068	2.079	9.092	16.199
3. H40	1,046	-0.770	2.939	17.444	27.335
4. H40 -BA	504	0.216	2.162	10.304	17.651
5. H20	1,004	-1.771	3.368	24.582	44.447
6. H20 -BA	488	0.136	2.539	14.111	17.651
7. D40	1,044	-0.075	2.697	13.438	19.364
8. D40 -BA	508	0.216	2.185	10.387	17.699
9. D20	993	-0.302	2.889	16.197	23.831
10. D20 -BA	490	0.499	2.430	13.764	17.699
11. H10 percent	850	1.612	3.765	30.214	37.129
12. H10 percent -BA	150	-0.192	2.705	17.684	16.219
13. DC and D40	940	-0.071	2.873	14.669	19.364
		Base age 50			
1. DC	986	-0.529	1.631	6.869	36.487
2. DC -BA	1,029	-0.401	1.686	6.076	14.557
3. H40	1,082	-0.889	1.837	6.796	11.983
4. H40 -BA	630	-0.042	1.703	6.782	15.197
5. H20	1,057	-1.038	2.112	9.062	16.659
6. H20 -BA	613	0.277	1.672	6.569	15.714
7. D40	1,061	-0.830	1.920	7.859	14.284
8. D40 -BA	629	-0.402	1.539	5.054	11.503
9. D20	1,029	-0.984	2.132	9.736	16.659
10. D20 -BA	627	-0.419	1.707	5.932	12.780
11. H10 percent	827	-0.631	2.362	19.425	34.560
12. H10 percent -BA	624	0.088	1.676	6.070	12.697
13. DC and D40	953	-0.857	1.878	7.754	14.284

DC = dominant and codominant trees; H40 = the 40 tallest trees per acre; H20 = the 20 tallest trees per acre; D40 = the 40 thickest trees per acre; D20 = the 20 thickest trees per acre; H10 percent = trees within 10 percent of maximum height on a plot; -BA = subpopulations that were defined at base age rather than anew at each measurement age.

The results for base age 50 were similar to the results for base age 25, except the benefit from defining the population at base age was greatly reduced. In fact, for the subpopulations defined by dominants and codominants, the subpopulation defined at base age had a higher mean absolute error than the subpopulation defined at each measurement. The error criteria differed little between these two subpopulations; a single observation with a large difference (36.487) more than explained the slightly greater mean squared error. Without that single observation, the mean squared error would decrease to 5.524. For base age 50, the overall best subpopulation had the 40 thickest trees at base age.

Because number of observations varied among subpopulations (table 1), some of these results could potentially be due to a small number of atypical observations in one subpopulation but not another. To lessen this contribution to the results, we recalculated the error criteria, but deleted those observations that had a missing value for either: subpopulation 1 or 7 (table 2), and subpopulation 2 or 8 (table 3).

For base age 25, results were similar among tables 1, 2, and 3. The subpopulations defined at base age were superior to their counterparts defined at each measurement. Among the subpopulations defined by base age, the subpopulation comprised of dominant and codominant trees was clearly the most efficient estimator for base age 25.

Table 2—Error criteria for site index predictions using 13 different subpopulations and 2 base ages (25 and 50)

Subpopulation	Observations	-bias	Mean error		Maximum difference
			Absolute	Squared	
	no.				
		Base age 25			
1. DC	811	0.579	2.740	13.895	15.885
2. DC -BA	490	0.234	2.295	10.429	16.199
3. H40	798	-0.720	3.298	20.409	27.335
4. H40 -BA	396	0.322	2.512	12.520	17.651
5. H20	764	-1.879	3.781	28.843	44.447
6. H20 -BA	384	0.158	2.981	17.293	17.651
7. D40	811	0.061	2.998	15.518	19.364
8. D40 -BA	396	0.321	2.504	12.414	17.700
9. D20	764	-0.175	3.209	18.829	23.831
10. D20 -BA	378	0.705	2.816	16.844	17.699
11. H10 percent	690	1.847	3.887	30.232	37.129
12. H10 percent -BA	105	0.081	3.160	22.182	16.219
13. DC and D40	811	0.064	2.970	15.521	19.364
		Base age 50			
1. DC	811	-0.592	1.615	5.827	13.301
2. DC -BA	777	-0.551	1.676	6.294	14.557
3. H40	808	-1.118	1.820	6.947	11.983
4. H40 -BA	548	-0.211	1.560	5.961	15.197
5. H20	798	-1.321	2.079	9.286	16.659
6. H20 -BA	534	0.088	1.538	5.822	15.714
7. D40	811	-1.021	1.947	8.403	14.284
8. D40 -BA	547	-0.477	1.459	4.666	11.503
9. D20	785	-1.136	2.102	9.764	16.659
10. D20 -BA	545	-0.477	1.617	5.470	12.780
11. H10 percent	645	-0.716	2.164	16.098	34.560
12. H10 percent -BA	545	0.028	1.594	5.732	12.697
13. DC and D40	810	-1.010	1.961	8.499	15.609

DC = dominant and codominant trees; H40 = the 40 tallest trees per acre; H20 = the 20 tallest trees per acre; D40 = the 40 thickest trees per acre; D20 = the 20 thickest trees per acre; H10 percent = trees within 10 percent of maximum height on a plot; -BA = subpopulations that were defined at base age rather than anew at each measurement age.

Observations were only included if they were not missing for subpopulation 1 and 7; other subpopulations could have missing observations.

Table 3—Error criteria for site index predictions using 13 different subpopulations and 2 base ages (25 and 50)

Subpopulation	Observations	-bias	Mean error		Maximum difference
			Absolute	Squared	
	no.				
		Base age 25			
1. DC	234	0.446	2.643	13.927	12.561
2. DC -BA	278	0.293	2.001	9.389	16.199
3. H40	276	-1.021	2.806	17.676	24.681
4. H40 -BA	274	0.472	2.189	10.742	17.651
5. H20	263	-2.063	3.454	30.423	44.447
6. H20 -BA	262	0.226	2.645	15.306	17.651
7. D40	274	-0.036	2.472	12.276	12.561
8. D40 -BA	278	0.520	2.281	11.630	17.700
9. D20	272	-0.311	2.582	14.147	13.095
10. D20 -BA	261	0.422	2.464	13.982	17.700
11. H10 percent	203	2.142	4.260	33.536	18.163
12. H10 percent -BA	44	-0.133	3.192	21.451	12.093
13. DC and D40	230	-0.135	2.804	14.313	12.561
		Base age 50			
1. DC	234	-0.452	1.428	4.682	10.073
2. DC -BA	278	-0.353	1.521	4.857	10.733
3. H40	277	-0.795	1.669	6.326	11.983
4. H40 -BA	278	0.374	1.925	8.345	15.197
5. H20	276	-1.024	1.975	8.787	15.714
6. H20 -BA	270	0.773	2.109	9.562	15.714
7. D40	277	-0.549	1.610	5.437	8.816
8. D40 -BA	278	-0.215	1.585	5.270	11.503
9. D20	274	-0.717	1.917	7.927	12.300
10. D20 -BA	277	-0.179	1.837	6.736	12.780
11. H10 percent	186	-0.328	2.022	15.790	26.485
12. H10 percent -BA	273	0.619	1.780	6.858	12.697
13. DC and D40	233	-0.622	1.600	5.587	8.816

DC = dominant and codominant trees; H40 = the 40 tallest trees per acre; H20 = the 20 tallest trees per acre; D40 = the 40 thickest trees per acre; D20 = the 20 thickest trees per acre; H10 percent = trees within 10 percent of maximum height on a plot; -BA = subpopulations that were defined at base age rather than anew at each measurement age.

Observations were only included if they were not missing for subpopulation 2 and 8; other subpopulations could have missing observations.

For base age 50, the results were much less consistent among tables 1, 2, and 3. The subpopulation defined at each measurement by the dominant and codominant trees (subpopulation 1) had the lowest mean absolute error in tables 1 and 3 and the lowest mean squared error in table 3. The subpopulation defined at base age by the 40 thickest trees per acre (subpopulation 8) had the lowest mean squared error in tables 1 and 2 and the lowest mean absolute error in table 2. Results for some subpopulations varied widely among tables 1, 2, and 3. The subpopulation defined at base age of the 20 tallest trees per acre varied from the largest mean absolute error (table 3) to the second lowest mean absolute error (table 2). Bias is sufficiently small for the subpopulations that have lower absolute and squared errors.

A major factor is the stability of the subpopulation over time. Figure 1 represents the change in rank of diameters for one plot over 40 years. Although rank for some trees is relatively unchanging, other trees change considerably over time (Tiarks and others 1998). For some of the trees, the change in rank is directional rather than simply fluctuating. For example, the tree that was initially the largest of the 25 trees fell to 14th rank and the tree that was initially 4th fell to 21st at the most recent measurement. On the other hand, a tree that was initially tied for 20th rank climbed to 9th, and a tree that was initially tied at the 15.5th rank climbed to the 5.5th at the most recent measurement. If rank is changing, clearly inclusion of a tree in the subpopulations will also be changing.

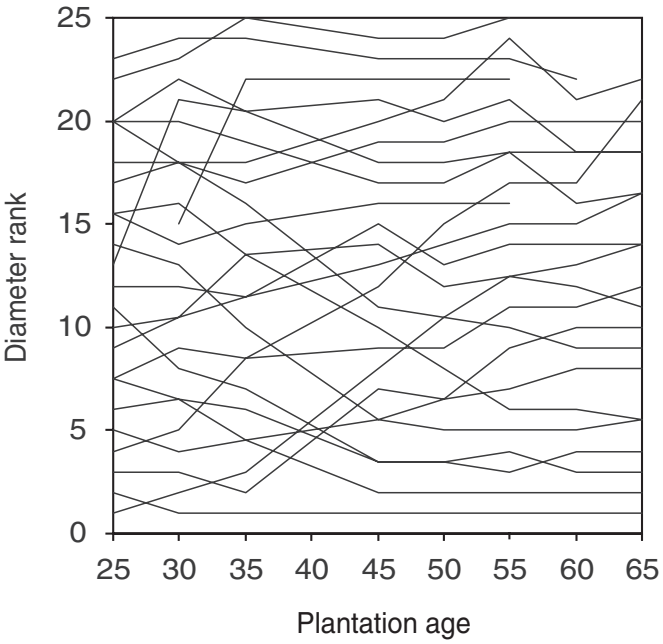

Figure 1—Change of rank in diameter for one arbitrarily selected plot. Each line represents a different tree. Trees present for three or fewer measurements are not included. If a line ends before age 65, the tree died.

The proportion of trees that changed in rank from one measurement to the next was significantly different between height and diameter (P much < 0.01) (table 4). Both height and diameter have more trees decreasing in percentile rank than increasing, an inevitable consequence of mortality of other trees on the plot. Percentile rank in diameter at breast height was much more stable than percentile rank in height. Ranks in height are less stable because height is measured with more error than diameter, and height can actually decrease if the top is damaged. Therefore subpopulations defined by diameter tend to have lower variation than the subpopulations defined by height.

For the frequency of trees that moved from one broad crown class to another during a measurement interval, there are significant differences between crown classes (P much < 0.01) (table 5). Unexpectedly, a higher proportion of intermediate and suppressed trees become dominant or codominant than the reverse. As there are more dominant and codominant trees than intermediate and suppressed, there is relatively little net change from measurement to measurement. Change from dominant and codominant trees arises from top damage or from neighbors asserting dominance. Change from intermediate and suppressed trees can occur when neighboring trees die or are harvested. However, much of the change may be explained by many trees being borderline between the crown classes, and the assignment of crown class may change due to different perspectives of different observers at different times. The stability of crown class designation from measurement to measurement, relative to the lower stability of rank of diameter and height, explains the effectiveness of the subpopulation defined at each measurement by the dominant and codominant trees.

Table 4—Percentage of trees changing in rank (expressed as classes of percentile change) for d.b.h. and height, between two successive measurements

Rank change	D.b.h.	Height
percentiles	*- - - - percent - - - -*	
< -17.5	5.4	9.6
-12.5 to -17.5	5.1	6.6
-7.5 to -12.5	10.0	10.0
-2.5 to -7.5	23.8	15.6
2.5 to -2.5	43.2	27.1
2.5 to 7.5	8.8	12.9
7.5 to 12.5	2.4	7.7
12.5 to 17.5	0.7	4.3
> 17.5	0.6	6.3

D.b.h. = diameter at breast height.

Table 5—Frequency in change of crown class between two successive measurements (two broad classes of crown class are used)

Crown class	Stays the same	Changes	Percent changing	Total
Dominant, codominant, or open grown	14,594	773	5.0	15,367
Intermediate or suppressed	6,486	649	9.1	7,135
Total	21,080	1,322		22,502

Sharma and others (2002) compared seven different definitions of top height based on crown class or rank in diameter and Lorey's mean height, which weights height by tree basal area. With regard to the consistency of S estimation over time, although the height of dominants and codominants that had always been such was superior to height of dominants and codominants at the time of measurement, the difference was small. Sharma and others (2002) did not consider the difficulty in applying such a definition in a S prediction context.

CONCLUSIONS

We chose to specify our site tree subpopulation as the dominant and codominant trees defined at each measurement age. There seems to be little benefit in restricting the subpopulations to those trees that always were dominant or codominant, particularly as that definition would greatly complicate the use of the site curves when predicting S. We chose the base age of 50 partly on these results. Given a base age of 25, our decision would have been to select one of the subpopulations defined at base age; they were superior when S was defined at this base age. It is reasonable to assume that most land managers will have rotations for longleaf pine that approach or exceed

50 years, so there is no real cost in utilizing the older base age. Our decision is made solely for our particular dataset. We suggest similar investigation when a S model is constructed for other species or regions.

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LOBLOLLY PINE SAPLINGS AFFECTED BY HURRICANE HUGO RETAINED GROWTH

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Abstract—This study evaluated the effectiveness of staking upright Hurricane Hugo-impacted, 3-year-old loblolly pine (*Pinus taeda* L.) saplings. Three replications of four combinations of site preparation and seedling-release treatments were installed in two clearcut areas in coastal South Carolina. Shortly after Hugo, saplings in a subplot within each treatment plot were staked upright, and the remaining saplings were not staked. The groundline diameter, diameter at breast height (d.b.h.), and total height were measured on unstaked trees between the eighth and ninth growing season following Hugo, and staked trees were measured during June and August of the ninth growing season after Hugo. Paired t-tests indicated that groundline diameter and d.b.h. were not significantly different between staked and unstaked saplings in any site preparation/release treatment in either area. The height of staked trees in plots site prepared by one-pass bedding in one area was significantly greater than unstaked trees in similar plots.

INTRODUCTION

Hurricane Hugo came ashore as a class 4 hurricane just north of Charleston, SC on September 21, 1989. The immediate tree damage was obvious; tree boles were broken, trees were tipped over without being broken, or there was major branch damage. Trees near the coast that remained standing received salt spray that killed the foliage. This damage was easily visible either immediately or shortly after the hurricane made landfall. Internal damage including wood shake, and twist was noticed in trees following Hurricane Camille (Nonnemacher 1970, Toulialos and Roth 1971) and later (Barry and others 2001), but little was found following Hurricane Hugo (Faust and others 1996). This external and internal damage is seen immediately after the storm or shortly afterward when the area is salvage logged, and the logs are sawn.

Little research has been reported on the long-term effect of a hurricane on tree growth. Gerhardt (1996) reported that in 5-year-old loblolly pine (*Pinus taeda* L.) plantations, severely leaning saplings grew less than saplings with less lean. The present research seeks to answer the question; do saplings with a hurricane-induced lean grow less than saplings without a lean? The ideal experiment to answer this question would involve monitoring leaning and straight saplings of the same age on the same site. However, if Hugo affected any saplings in a plantation, then all the saplings were affected, thus not allowing a comparison. MeadWestvaco personnel did stake upright sets of saplings in Hurricane Hugo-damaged young loblolly pine plantations, and I measured the staked and adjacent unstaked saplings eight growing seasons later. The purpose of this research was to compare the groundline diameter, diameter at breast height (d.b.h.), and total height of staked upright and unstaked saplings, in plots established with a range of site-preparation techniques.

STUDY AREAS

Two loblolly pine plantations in South Carolina's outer Coastal Plain were selected for study. The Snow Mill plantation is in northern Georgetown County, about 4.4 km northwest of Plantersville. This area is on the Pamlico terrace and is in the Atlantic Coastal Flatwoods section, Lower Terraces subsection (Keys and others 1995). The soil is a poorly drained Bladen loam, a clayey, mixed, thermic Typic Albaquult (Stuckey 1982). The 25-year site index of the first rotation, intensively site-prepared, P-fertilized, unthinned, loblolly pine plantation was 24.4 to 25.9 m (Trousdell and others 1974) or 22.9 to 24.4 m (Pienaar and Shiver 1980). Mild winters and hot humid summers characterize the Georgetown area climate. January air temperature averaged 9.0 °C, August temperature averaged 26.8 °C, and mean annual precipitation averaged 1315 mm for the period 1930 -95 (temperatures) or 1930 -96 (precipitation).

The Greeleyville plantation is in southwestern Williamsburg County, about 3.5 km east-northeast of Greeleyville. This plantation is on the Talbot terrace and is located in the Atlantic Coastal Flatwoods section, Upper Terraces subsection (Keys and others 1995). The soil is a somewhat poorlydrained Lynchburg fine sandy loam, a siliceous, thermic Aeric Paleaquult (Ward 1989). The 25-year site index of the first rotation, intensively site-prepared, P-fertilized, unthinned, loblolly pine plantation was 21.3 to 22.9 m (Trousdell and others 1974) or 19.8 to 21.3 m (Pienaar and Shiver 1980).

The Snow Mill plantation was clearcut harvested and burned in June 1986, and three replications of the site preparation treatments were installed in July 1987. Site preparation treatments were: preplanting proprietary herbicide treatment of all residual stems (herbicide), rebed over old beds (rebed-with), rebed perpendicular to old beds (rebed-perpendicular), and three-pass shear, rake, and bed (intensive). The Greeleyville plantation was clearcut and burned in July 1987, and three replications of the site-preparation treatments were installed in August 1987. Site-preparation treatments consisted of: preplanting proprietary site-preparation herbicide treatment of residual stems (herbicide), rebed over old beds (rebed-with), and three-pass shear, rake, and bed (intensive). Both plantations were planted on a 1.8-m spacing along the old or new beds, with improved, coastal, 1-0, bare-root loblolly pine in

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

December 1987. Each treatment plot was split, and a proprietary chemical release treatment was applied to one-half of each plot during the spring and summer of the first growing season following planting. Neither plantation was fertilized. The eye of Hurricane Hugo passed within 80 km of the Snow Mill area and within 27 km of the Greeleyville area on September 22, 1989, which was 2 growing seasons following planting.

METHODS

There were 30 saplings in each treatment plot; half were righted and attached to oak stakes in the winter of 1989. The remaining saplings in each plot were left as they leaned. In December 1997, 8 growing seasons after Hugo, 15 unstaked saplings per treatment plot were measured, and, in June through August 1998, 8.5 growing seasons since Hugo, 7 staked saplings per treatment plot were measured. Diameter at groundline, d.b.h., and total height were measured with either a diameter tape or sectional aluminum poles with an attached fiberglass tape. We measured saplings in the released and unreleased halves of the herbicide site-preparation treatment, and unreleased only half of the rebed-with, rebed-perpendicular, and intensive site-preparation plots. The measurements were averaged for each plot to produce three paired (staked and unstaked) values for each treatment measured in each stand. Paired t-tests with Bonferroni-adjusted probabilities were used to test for a difference due to staking.

RESULTS

Table 1 summarizes the parameter averages, standard errors, and t-test probabilities by metric, site-preparation treatment, and stand. Groundline diameter was greater for the unstaked saplings in three of the four treatments in Snow Mill and showed no pattern in the Greeleyville treatments. No differences were significant. Breast-height diameters were very similar in each stand for the staked and unstaked saplings,and no differences were significant. Heights were greater for the staked saplings compared to the unstaked, and the difference was significant for the saplings in the rebed site-preparation plots of Greeleyville.

DISCUSSION

These results are biased because only those saplings that survived eight growing seasons after Hugo were measured. A more complete description of the long-term damage from Hugo would incorporate survival. The only significant difference between staked and unstaked saplings was the total height of Greeleyville saplings in the rebedded plot. The other 23 comparisons were not significant. From this

Table 1—Average (and standard error of the mean) groundline diameter, d.b.h., total height, and t-test P values for staked and unstaked saplings in the Snow Mill and Greeleyville plantations eight growing seasons after Hurricane Hugo passed nearby when the saplings were 3 years old

		Site preparation and release treatment			
Stand	Condition	Intensive unreleased	Rebed unreleased	Herbicide unreleased	Herbicide released
		Groundline diameter (cm)			
Snow Mill	Staked	6.5 (1.8)	19.4 (1.5)	20.6 (1.2)	19.8 (1.3)
	Unstaked	19.8 (2.1)	20.7 (0.7)	19.6 (1.2)	21.1 (0.2)
	P-value	0.16	0.32	0.67	0.46
Greeley-ville	Staked	18.9 (0.6)	16.7 (0.4)	14.2 (0.7)	16.3 (2.5)
	Unstaked	17.0 (1.4)	17.4 (0.0)	14.2 (0.6)	16.2 (0.6)
	P-value	0.13	0.19	0.98	0.96
		Diameter at breast height (cm)			
Snow Mill	Staked	11.6 (1.7)	15.1 (1.2)	15.7 (0.5)	14.4 (1.0)
	Unstaked	14.1 (1.7)	15.1 (0.5)	14.1 (0.8)	14.5 (0.4)
	P-value	0.15	0.97	0.38	0.97
Greeley-ville	Staked	14.3 (0.4)	12.7 (0.4)	10.5 (0.8)	11.9 (2.0)
	Unstaked	12.7 (1.1)	13.6 (0.1)	10.5 (0.2)	11.9 (0.4)
	P-value	0.29	0.18	1.0	1.0
		Total height (m)			
Snow Mill	Staked	9.2 (1.4)	12.4 (0.5)	11.4 (0.5)	11.2 (0.7)
	Unstaked	10.1 (1.3)	10.9 (0.5)	10.3 (0.8)	10.4 (0.5)
	P-value	0.13	0.13	0.29	0.55
Greeley-ville	Staked	12.2 (0.6)	12.0 (0.2)	8.7 (0.8)	9.5 (1.1)
	Unstaked	10.8 (0.2)	10.9 (0.2)	7.8 (0.2)	8.9 (0.2)
	P-value	0.21	0.01	0.41	0.67

we can conclude that either there truly was no effect after eight growing seasons, or that the combination of natural variation and sampling error was greater than the hurricane's effect. Comparing the standard error of staked saplings (which was calculated from 3 plot means, each the average of 7 saplings) to the standard error of unstaked saplings (calculated from 3 plot means, each the average of 15 saplings) indicated that neither sample size had consistently higher or lower errors. Thus, it appears that if there was an effect of the hurricane, it was small in comparison to the natural variation in each treatment plot.

MANAGEMENT IMPLICATIONS

Two 'take home' points can be drawn from these results. First, remedial actions following the hurricane, like staking the saplings upright, is not clearly effective and is feasible only on small tracts. Staking saplings upright on large tracts would be labor intensive and probably not profitable. Secondly, saplings left in a leaning (ca. 45 degrees) position following a hurricane do not lose measurable growth compared to those staked upright immediately after the hurricane. It is quite possible that leaning saplings will grow slower than those not impacted by a hurricane, perhaps due to being whipped back and forth, but this conjecture is beyond these data. From personal observation of saplings in both stands, there is a noticeable crook at the base of many trees, indicating that the trees were once leaning and have since righted themselves. The growth rings of one of these saplings in the region of the crook showed the classic compression wood response.

ACKNOWLEDGMENTS

MeadWestvaco Corporation provided the research sites and early funding that made this project possible.

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IMPACT OF EARLY PRUNING AND THINNING ON LUMBER GRADE YIELD FROM LOBLOLLY PINE

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Abstract—The Sudden Sawlog Study was established in 1954 near Crossett, AR, in a 9-year-old loblolly pine plantation to test the hypothesis that loblolly plantations can produce sawtimber in 30 years. To stimulate diameter and height growth and clear wood production, study plots were heavily thinned, trees pruned to 33 feet by age 24 years, understory mowed, and growth of intensively managed trees compared with control trees. The study was officially closed at age 33 when it was reported that, with intensive management on good sites, loblolly pine can produce sawtimber-size trees in 30 years. The intensively managed and unpruned control trees were harvested in 2001 and the butt two logs of each tree sawn into lumber. At harvest, average diameter at breast height was 22.4 inches on plots receiving intensive treatments compared with 16.1 inches for controls. A portion of the intensively managed and control trees were sawn at a dimension sawmill and a portion sawn at a shop sawmill. Starting at age 9, trees were pruned every 3 years to one-half total height; by age 15 they were pruned to 20 feet and thinned to 100 trees per acre or less. These practices significantly increased the yield of high-grade lumber from butt logs sawn at the dimension and shop sawmills. Pruning every 3 years to one-half total height to 33 feet by age 24 and continued thinning resulted in a large-diameter knotty core in the second log that significantly reduced lumber grade. To reduce the diameter of this knotty core, when loblolly pine is thinned to < 100 trees per acre by age 15, crop trees should be aggressively pruned to 34 feet, either by frequent pruning or pruning to a shorter live crown of 33 to 40 percent with a minimum stem diameter of 2 inches at base of crown. To maximize lumber value, pruned logs should be sawn into shop lumber.

INTRODUCTION

To test the hypothesis that loblolly pine (*Pinus taeda* L.) plantations can produce sawtimber in 30 years, the Sudden Sawlog Study was established in 1954 near Crossett, AR (Burton 1982). The study was established in a 9-year-old loblolly pine plantation hand-planted in 1945 on an old cotton field at a spacing of 6 feet by 6 feet [1,210 trees per acre (TPA)]. The site index for the plantation was projected to be between 90 and 100 feet at age 50 years, and in 1954 average stocking was 1,100 TPA. The original objective of the study was "to determine whether a plantation on a good site (SI = 90) could be managed to produce good quality sawtimber on a short rotation by combining early thinning, understory vegetation control and pruning" (Baker and Bishop 1986).

To stimulate diameter growth, height growth, and clear wood production, researchers thinned study plots, controlled understory growth, pruned trees, and compared growth to control plots. The study imposed the following treatments.

- Sawtimber-only: all noncrop trees and all but 100 crop TPA were cut at age 9. Stands were thinned every 3 years thereafter to 76 TPA by age 19 and to 41 TPA at age 30
- Sawtimber-pulpwood: thinnings at age 9 and 12 removed noncrop trees with crowns within 5 feet of crowns of 100 crop trees. The last noncrop trees were removed at age 15. Continued thinnings at 3-year intervals left 80 TPA at age 19 and 52 TPA at age 30
- Sawtimber-delayed: stands were thinned to 100 crop TPA at age 12 and thinned every 3 years thereafter until 45 TPA remained at age 30
- Control: plots were thinned, mainly from below, to a basal area of 85 square feet per acre at age 12 and every 3 years afterward though age 30. The thinnings reduced stand density from 712 stems per acre at age 12 to 116 stems per acre at age 30.

The four treatments were installed on 0.25-acre plots and replicated three times in randomized blocks. Crop trees in the intensively managed sawtimber only, sawtimber pulpwood, and sawtimber-delayed plots were pruned from the ground to about one-half total height after the first thinning at age 9 and every 3 years afterward until clear length averaged 33 feet at age 24. The severity and timing of later thinnings were based on periodic growth in diameter at breast height (d.b.h.). Beginning at age 19, the woody understory was mowed every 2 years in the intensively managed plots.

Numerous researchers have published findings based on the Sudden Sawlog Study. Burton and Shoulders (1974) reported that at age 21 the saw log-only treatment produced the greatest sawtimber volume and lowest returns from thinnings. They also reported that the sawtimber-delay treatment produced the largest early return from thinnings and largest yield of sawtimber at age 27. However, if maximum fiber production was the objective, the control treatment would produce 35 to 66 percent more merchantable cubic volume through age 27 than any of the

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

intensive treatments. At age 33, average d.b.h. was 17.1 to 18.0 inches in the intensive treatments compared with 12.3 in the controls; therefore, loblolly pine plantations can produce sawtimber on good sites in 30 years (Burton 1982). Burton (1982) also found that the intensive treatments' advantages over control in sawtimber yield to an 8-inch top rapidly diminished after age 30. Conventional saw-log yield from intensive treatments was six times that of control at age 24, 2.4 times at age 27, 2.3 times at age 30, and only 1.5 times at age 33.

The study was officially closed at age 33; however, thestands were never cut, and the trees were remeasured at ages 36, 39, and 45. At age 45, average Doyle board-foot volume per acre for all treatments was not significantly different (Baldwin and others 1998). However, the average d.b.h. of the trees that received the intense treatments (20.4 inches) was 38 percent larger than that of the control trees (14.9 inches). Baldwin and others (1998) reported that after 33 years, the control treatments led all other treatments in predicted financial returns, and throughout the study the controls produced the greatest cubic-foot volume. At age 45, basal area of the control trees was about 30 square feet per acre more than the sawtimber-pulp treatment (109 square feet) and 40 square feet per acre more than the sawtimber-only (98 square feet) and sawtimber-delay (102 square feet) treatments. At age 48, five trees were harvested from the saw log-only plots to examine the effect of intensive treatments on yield and quality of veneer (Groom and others 2002). Their results show the intensive plantation trees produced the lowest quality veneer, both in terms of visual and ultrasonic grade, when compared with veneer produced from 48-year conventional plantations, natural regeneration, and uneven-aged stands.

The objective of this study was to determine the impact of the sawtimber-only, sawtimber-pulp, sawtimber-delay, and control treatments on dimension and shop lumber grade yields produced from the Sudden Sawlog Study trees.

METHODS

In October 2001, at plantation age of 57, we harvested the remaining 167 Sudden Sawlog Study trees (table 1). The trees were felled using a saw-head feller buncher. A stratified random sample of seven trees per d.b.h. class from 12 to 20 inches for controls and from 20 to 26 inches for intensively managed trees were measured in detail. After felling, taper measurements were collected at 2-foot intervals from the butt to the tip on 8 sawtimber-only, 10 sawtimber-pulp, 12 sawtimber-delay, and 34 control trees. On trees measured in detail, diameter and location of dead and live branches were recorded for the butt 50 feet up the stem. Taper measurements were also collected at 2-foot intervals on the butt 33 feet on all trees not measured in detail.

Table 1—Average tree characteristics by treatment for 57-year sudden saw log loblolly pine harvested

	Treatment			
	Sawtimber			
Tree characteristics	Only	Pulp	Decay	Control
Trees harvested	23	34	33	77
D.b.h. (*inches*)	22.9	21.5	21.8	16.1
Total height (*feet*)	99	101	103	103
Form class	82	82	83	83
Sawlog volume (*cubic feet*)[a]	67.2	59.6	61.7	34.0

[a] Butt two saw logs only.

Two 16.4-foot saw logs were cut from the butt of each tree and identified by tree number and log number. The ends of each log were painted with a color-and-pattern combination to identify each log to tree and log position. A subsample, stratified by d.b.h. class of 30 trees harvested from intensively managed plots and 47 trees harvested from control plots, were sawn into dimension lumber at a conventional pine-band-dimension sawmill. The dimension mill produced 8 by 4 dimension lumber and 4 by 4 boards. A second subsample of 60 trees from intensively managed plots and 30 trees from control plots were sawn into shop lumber at a shop sawmill equipped with a band-head rig. The shop sawmill produced 5 by 4 shop or factory lumber, 4 by 4 boards, and 8 by 4 dimension lumber. After kiln drying and planning, the lumber was graded by certified lumber graders using rules of the Southern Pine Inspection Bureau (1994). Lumber was pencil-trimmed during grading to retain paint on the ends of each board in order to identify the tree and log from which the piece was sawn. The wholesale value of lumber produced from each tree was determined based on southern pine November 2002 average Random Lengths (Elmore 2002) prices. Lumber prices for radiata pine were used for southern pine molding grades. The value of each board was calculated based on its size, length, and lumber grade.

On the intensively managed crop trees, the d.b.h. and total height data collected every 3 years from age 9 through age 24 was used to estimate diameter of the knotty core. It was assumed that each tree was pruned to one-half of its total height every 3 years starting at age 9. Based on this assumption, taper functions were used to estimate the diameter outside bark at the base of the crown after each pruning lift using d.b.h. and total height as independent variables.

RESULTS

The d.b.h. of trees harvested from the intensively managed plots was 37 percent larger than that of the trees harvested from the control plots (table 1). Total height did not vary significantly among treatments and averaged 101 feet. Girard form class averaged 82 and did not vary significantly with treatment. The average small-end diameter of the logs processed in the dimension sawmill was similar to that of the logs processed in the shop sawmill (table 2). Board-foot volume of lumber produced per cubic foot of saw log input [lumber recovery factor (LRF)] for the dimension mill (8.4 board feet per cubic foot) was on average 18 percent higher than that of the shop mill (7.1 board feet per cubic foot). The shop sawmill had a lower LRF because it produced 57 percent 4 by 4 and 5 by 4 lumber, requiring more saw cuts and resulting in a higher proportion of each log being processed into sawdust (table 3). The dimension sawmill

Table 2—Average saw log small end diameter, cubic volume, board feet of lumber produced, and lumber recovery factor by treatment and log position for trees sawn in dimension and shop sawmills

Log characteristic	Intensively managed		Control	
	Butt log	Second log	Butt log	Second log
		Dimension sawmill		
Logs sawn (*no.*)	30	30	47	47
SED *(inches)*	18.5	17.3	13.4	12.4
Volume (*cubic feet*)	21.2	16.2	10.3	8.8
Lumber (*bf*)[a]	311	239	151	129
LRF (*bf/cubic foot*)	8.7	8.3	8.2	8.4
		Shop sawmill		
Logs sawn (*no.*)	60	60	30	30
SED (*inches*)	17.9	16.7	13.4	12.4
Volume (*cubic feet*)	18.9	16.2	11.1	9.0
Lumber (*bf*)[a]	220	199	136	114
LRF (*bf/cubic foot*)	6.5	7.3	7.1	7.4

SED = small end diameter; LRF = lumber recovery factor.
[a] Mill tally.

Table 3—Proportion of lumber produced by lumber thickness by treatment and log position for 57-year sudden saw log loblolly pine sawn at a dimension sawmill compared to a shop sawmill

Lumber thickness	Intensively managed		Control	
	Butt log	Second log	Butt log	Second log
inches	- - - - - - - - - - - - - - - *percent* - - - - - - - - - - - - - - -			
		Dimension sawmill		
4 by 4	3	1	1	0
5 by 4	0	0	0	0
8 by 4	97	99	99	100
		Shop sawmill		
4 by 4	7	7	29	26
5 by 4	65	47	28	18
8 by 4	28	46	43	56

averaged 99 percent 8 by 4 lumber and 1 percent 4 by 4 lumber. From the intensively managed trees sawn in the shop sawmill, the average LRF for butt logs was lower than that of the other logs because they produced 72 percent of their lumber in 4 by 4 and 5 by 4 boards.

The proportion of dimension lumber sawn into different lumber widths differed significantly between the intensively managed and control trees because of the significant difference in small-end diameter between treatments (table 4). The intensively managed trees sawn at the dimension sawmill produced on average 67 percent 2 by 12s and only

Table 4—Average distribution of lumber by lumber width by treatment and log position for 57-year loblolly sawn at a dimension sawmill

Treatment	Lumber width *(inches)*									
	Butt log					Second log				
	4	6	8	10	12	4	6	8	10	12
	- - - - - - - - - - - - *percent* - - - - - - - - - - - -									
Sawtimber only	1	3	8	24	64	5	2	9	27	57
Sawtimber pulp	3	2	7	16	72	6	1	6	19	68
Sawtimber delay	1	5	9	24	61	6	1	6	5	82
Control	4	7	17	56	16	3	10	21	50	16

19 percent 2 by 10s, compared with the control trees that produced only 16 percent 2 by 12s and 53 percent 2 by 10s.

Pruning to one-half of total height by age 15 resulted in the butt logs from intensively managed trees sawn in the dimension sawmill yielding a higher proportion of No. 1 & Btr and a lower proportion of No. 2 lumber than that of controls (table 5). Pruning to 33 feet by age 24, however, did not result in an increase in proportion of No. 1 & Btr lumber produced from the second log of intensively managed trees sawn in the dimension sawmill compared to that of controls. In fact, thinning the stand and pruning the second log yielded a significant decrease in proportion of No. 1 & Btr and increase in the proportion of No. 3 lumber compared with that of the unpruned controls. Pruning the second log at later ages after thinning resulted in a large-diameter knotty core in the second log (fig. 1). The average diameter of the knotty core was generally < 6.0 inches in the butt pruned log compared with 9.5 inches at the top of the second log. Thinning the intensively managed stands to < 100 TPA at

Table 5—Proportion of lumber produced by lumber grade by treatment and log position for 57-year sudden saw log loblolly pine sawn at a dimension sawmill

Lumber grade	Treatment			
	Sawtimber			
	Only	Pulp	Decay	Control
	percent			
Butt log				
C & D	3	3	2	1
No. 1 & Btr	56	72	62	54
No. 2	37	20	32	40
No. 3	4	4	3	3
No. 4	0	1	2	2
Second log				
C & D	0	0	0	0
No. 1 & Btr	7	8	11	16
No. 2	58	74	61	71
No. 3	35	15	26	10
No. 4	0	4	2	3

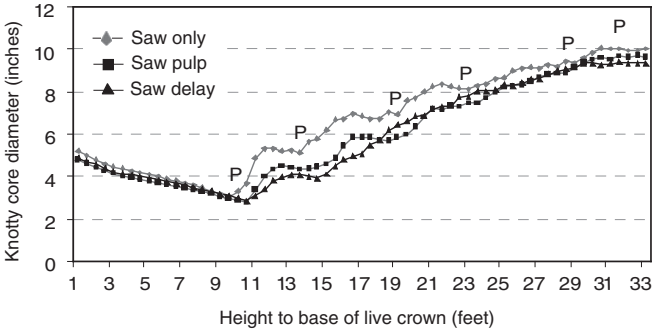

Figure 1—Average diameter of knotty core at base of live crown after pruning lift (P) by treatment for loblolly pine Sudden Sawlog Study trees.

age 15 and pruning to one-half of total height in 3-year intervals delayed crown closure and stimulated stem diameter and branch growth at the base of the crown, resulting in lower grade lumber in the second log.

Based on the literature, loblolly pine will respond well to release if the trees have a minimum diameter of 2 inches at the base of the live crown and > 20 percent live crown (McLemore 1987). Thus, to reduce the diameter of the knotty core, it appears that loblolly pine should be pruned as early as possible to 17 feet in the first lift and to 34 feet in the second lift. Pruning should occur as soon as the trees are large enough to maintain 33 to 40 percent live crown and have a diameter at the base of the live crown > 2 inches.

Although the objective of the Sudden Sawlog Study was to prune to a height of two 16-foot saw logs plus trim (Burton 1982), a few of the trees were apparently not pruned up to 33 feet on the intensively managed plots. Based on the live and dead branch data collected on 31 intensively managed trees, 13 of the trees had live branches at 31 feet (table 6). The average diameter of the knots in the second log was larger than the average diameter of the knots in control trees. The wide spacing of crop trees on the intensively managed plots stimulated branch growth in the third log. On average the third log of the intensively managed trees contained twice as many branches as that of the controls, and the branches were on average 50 percent larger in diameter. The average maximum size knot on the third log was > 70 percent larger on the intensively managed trees compared with the control trees.

The butt logs of intensively managed trees, sawn in the shop sawmill, produced on average 190 percent more of their lumber in molding-grade boards compared with the butt log of the controls (table 7). However, the control butt logs sawn in the shop sawmill yielded significantly more 4 by 4 C&D boards than the intensively managed trees. The butt logs of the intensively managed and control trees both yielded very little No. 3 or No. 4 lumber.

Table 6—Summary of live and dead knots by treatment and log position for 57-year sudden saw log loblolly pine trees

Log position	Logs sampled	Logs with knots	Knots per log	Average knot diameter	Average maximum knot diameter	Average height of knot
	no.			*inches*		*feet*
Intensively managed						
Butt	31	0	0	—	—	—
Second	31	13	2	2.3	2.4	31
Third	31	31	15	2.7	4.1	42
Control						
Butt	34	1	2	1.0	1.0	7
Second	34	8	1	1.5	1.5	31
Third	34	32	7	1.8	2.4	45

Table 7—Proportion of lumber produced by lumber grade by treatment and log position for 57-year sudden saw log loblolly pine sawn at a shop sawmill

Lumber grade	Treatment			
	Sawtimber			
	Only	Pulp	Decay	Control
	- - - - - - - - - - *percent* - - - - - - - - -
Butt log				
Molding	60	56	60	20
C & D	3	5	6	25
No. 1	8	20	11	16
No. 2	26	15	20	38
No. 3	3	4	3	1
No. 4	0	0	0	0
Second log				
Molding	15	10	16	7
C & D	6	5	6	13
No. 1	30	32	30	16
No. 2	19	26	28	53
No. 3	28	25	18	10
No. 4	2	2	2	1

Table 8—Average value of lumber per 1,000 board feet mill tally and 100 cubic feet of saw log by treatment and log position for 57-year sudden saw log and 57-year loblolly pine sawn at dimension and shop sawmills

Log position	Treatment			
	Sawtimber			
	Only	Pulp	Delay	Control
Dimension sawmill (*dollars per 1,000 board feet*)				
Butt	378 (14)[a]	386 (17)	371 (12)	331
Second	313 (1)	336 (9)	337 (9)	309
Shop *sawmill (dollars per 1,000 board feet*)				
Butt	816 (36)	806 (34)	818 (36)	600
Second	582 (28	544 (20)	591 (30)	455
Dimension sawmill (*dollars per 100 cubic feet*)				
Butt	338 (24)	337 (23)	320 (18)	272
Second	249 (-5)	282 (8)	284 (8)	262
Shop sawmill (*dollars per 100 cubic feet*)				
Butt	530 (24)	522 (22)	530 (24)	427
Second	428 (27)	409 (21)	414 (23)	337

[a] Percent difference from control.

The proportion of lumber sawn in the shop sawmill from the second log of intensively managed trees that graded molding or No. 1 was on average twice that of controls (table 7). However, the second log of intensively managed trees yielded on average only 24 percent in No. 2 compared with 53 percent for the controls and 24 percent in No. 3 compared with 10 percent for the controls. The significant reduction in proportion of No. 2 and significant increase in No. 3 lumber produced from the second log of intensively managed trees is the direct result of the large knotty core (fig. 1) and a few large unpruned branches at the top of the second log (table 6).

The wholesale value of lumber per 100 cubic feet of log input for butt logs from intensively managed trees sawn at the dimension mill was on average 22 percent higher than that of the controls (table 8). However, the lumber value per 100 cubic feet of log input for the second logs from the intensively managed trees increased an average of only 4 percent over that of the controls. The value of lumber per 100 cubic feet of log input was 13 percent lower for the second logs compared with that of the butt logs for the intensively managed trees sawn at the dimension sawmill. The value of lumber per 100 cubic feet for the second log was reduced because the large diameter of the knotty core increased production of No. 3 lumber from the second log.

The value of lumber produced per 100 cubic feet of log input for the intensively managed trees sawn at the shop mill was on average 23 percent higher than that of the controls for both the butt and second logs (table 8). The large knotty core in the second log of the intensively managed trees, however, reduced the value of lumber per 100 cubic feet of log input by 19 percent in the second log compared with the butt log.

The value of lumber per 100 cubic feet of tree input averaged $305 per 100 cubic feet for intensively managed trees sawn at the dimension sawmill or 14 percent higher than for the control trees ($267 per 100 cubic feet). The value of lumber per 100 cubic feet of tree input for intensively managed trees sawn at the shop sawmill averaged $477 per 100 cubic feet or 23 percent higher than the control trees ($388 per 100 cubic feet). The value of lumber per 100 cubic feet of tree input averaged 56 percent higher for intensively managed trees sawn at the shop sawmill compared with intensively managed trees sawn at the dimension sawmill.

SUMMARY AND CONCLUSIONS

Pruning every 3 years to one-half total height starting at age 9, to 20 feet by age 15, and thinning to 100 TPA or less by age 15 significantly increased the yield of high-grade lumber from butt logs. The intensively managed butt logs sawn at the shop sawmill produced 59 percent molding lumber compared with only 20 percent for that of the controls. The intensively managed butt logs sawn at the dimension sawmill yielded 63 percent No. 1 & Btr compared with 54 percent for the controls. The value of lumber per 100 cubic feet of log input was 23 percent higher for intensively managed butt logs sawn at the shop sawmill compared to controls and 22 higher for intensively managed butt logs sawn at the dimension sawmill compared to controls.

The Sudden Sawlog Study intensive treatments resulted in the greatest increase in lumber value when intensively managed butt logs were sawn at the shop sawmill. The average value of lumber from intensively managed butt logs sawn at the shop sawmill was $813 per 1,000 board feet or 115 percent higher than intensively managed butt logs ($378 per 1,000 board feet) sawn at the dimension sawmill.

Pruning every 3 years to one-half total height to 33 feet by age 24 and continued thinning resulted in a large-diameter knotty core in the second log that reduced lumber grade. The average value of lumber per 100 cubic feet of log input for intensively managed second logs sawn at the shop sawmill was 24 percent higher compared with controls. However, the value of lumber per 1,000 board feet from second logs was 42 percent less than that from the intensively managed butt logs. The average value of lumber per 100 cubic feet of log input for intensively managed second logs sawn at the dimension mill was only 4 percent higher than that of the controls, and the value of lumber per 1,000 board feet from second logs was 15 percent less than that of the intensively managed butt logs. Thinning to 53 TPA or less by age 30 and pruning to 33 feet by age 24 slowed crown closure and stimulated branch growth in the third log. Therefore, pruning only the butt 17 feet would probably stimulate growth of large branches in the second log and reduce lumber grade yield.

When loblolly pine is thinned to < 100 TPA by age 15, crop trees should be aggressively pruned to 34 feet either by frequent pruning or pruning to a shorter live crown of 33 to 40 percent with a minimum stem diameter of 2 inches at base of crown to reduce the diameter of the knotty core in the second log. To maximize lumber value, pruned logs should be sawn into shop lumber.

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FOLIAGE DENSITY DISTRIBUTION AND PREDICTION OF INTENSIVELY MANAGED LOBLOLLY PINE

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Abstract—The pipe model theory says that foliage biomass is proportional to the sapwood area at the base of the live crown. This knowledge was incorporated in an effort to develop a foliage biomass prediction model from integrating a stipulated foliage biomass distribution function within the crown. This model was parameterized using data collected from intensively managed loblolly pine (*Pinus taeda* L.) plantations in the Lower Coastal Plain and Piedmont of Georgia and validated using litter trap data. Using readily obtained mensuration predictors—crown length and crown height, and diameter outside bark at the base of the live crown, this model can predict total foliage biomass and the foliage biomass for any piece of the crown.

INTRODUCTION

Continuous functions such as the Weibull (Bailey and Dell 1973) and Beta have been applied for predicting foliage biomass distribution within the crown (Baldwin and others 1997, Gillespie and others 1994, Vose 1988, Xu and Harrington 1998, Yang and others 1999). Predictors employed for this purpose are some tree and crown characteristics such as diameter at breast height (d.b.h., cm) and crown length (l, m). However, most of these studies were targeted to predict foliage biomass distribution on individual branches rather than tree level foliage and branch biomass prediction models, which restricts our ability to predict whole tree biomass and to evaluate morphological relationships among different tree components.

In this study, a foliage biomass prediction model was derived using a proposed distribution pattern in the crown, and a branch biomass prediction model was obtained based on a strong linear relationship between foliage and branch biomass. A key predictor, diameter outside bark at the base of the live crown (d.o.b., cm) was introduced to our prediction models because of a suggested relationship between foliage biomass and crown basal area; i.e., foliage biomass is proportional to the sapwood area at the base of the live crown from the pipe model theory (Causton 1985, Shinozaki and others 1964, Valentine and others 1994, Waring and others 1982). Other predictors employed were crown length (l, m) and crown height (ch, m). The impacts of cultural treatments were evaluated during parameterization using data collected from destructively sampled trees. Because the dependent variables involved are closely related and because foliage and branch biomass have high variability from site to site, a joint mixed-effects modeling approach was employed for parameter estimation to obtain consistent and unbiased estimates.

DATA COLLECTION AND DESCRIPTIVE ANALYSIS

Our data were collected from intensively managed loblolly pine (*Pinus taeda* L.) stands in the Piedmont (PID) and the Lower Coastal Plain (LCP) of Georgia. The Lower Coastal Plain installations had six blocks (two established in each year—1987, 1989, and 1993) and the Piedmont locations had five blocks (two established in 1988, two in 1990, and one in 1995) in which four 0.15-ha treatment plots were assigned one of four treatments: (1) complete vegetation control (controlling competing woody and herbaceous vegetation using herbicides [H]), (2) fertilization [F], (3) complete vegetation control and fertilization [HF], and (4) control [C] (Borders and Bailey 2001).

In the winter of 1999 (January), 192 trees were harvested from the Lower Coastal Plain installations for research on foliage, branch, and stem biomass. At each installation two blocks were 12 years old, two were 10 years old, and two were 6 years old at time of harvest. Similarly,160 sample trees were harvested from the Piedmont installations during the winter of 2000 (January) when the ages were 12, 10, and 5 years old, respectively.

For each fallen tree, we measured branch diameter at the base next to the bole and branch height from stump for all live branches. We also obtained green weight of all branches and foliage for each tree. A single live branch from each whorl was randomly sampled. For this sub-sample of branches, we measured total length, length to foliage from base of branch, green weight, and dry weight. In addition, for each of these sample branches, we took a composite subsample of 40 to 50 fascicles along the length of the branch. We determined the green weight, dry weight, and projected leaf area for each of these foliage samples.

In addition, we collected litterfall at approximately 6-week intervals between March 1999 and March 2001 from five 0.75-diameter round litter traps randomly placed in each plot. Litter collected from each plot was pooled and oven dried at 60 °C. Pine leaf litter was separated from the rest of the sample and weighed. Specific leaf area of the litter was determined individually for all plots using a subsample of litter. The amount that fresh needles shrank before abscission was determined empirically and used to convert litter area to that of fresh needles. Leaf biomass of fresh needles was then determined by multiplying leaf area by the inverse of specific leaf area of fresh needles. Specific leaf area of fresh needles was measured 7 times during the growing season and averaged to determine specific leaf areas for each location, age, and treatment combina-

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

tion. At the time of harvest, the majority of year-old foliage had abscised. Therefore, the litter collected between March 1999 and March 2000 represents the foliage on the trees at the time of the harvest at the LCP installation (winter 1999), and the litter collected between March 2000 and March 2001 represents the foliage on the trees at the time of the harvest at the PID installation (winter 2000) (Will and others 2002).

MODEL DERIVATION

The approach employed is to derive a foliage prediction equation from its distribution function. In this approach, a mechanically reasonable model structure can be constructed based on the relationship between foliage biomass and crown characteristics. It was assumed that foliage biomass is uniformly distributed in cross-sectional areas of the crown with a distribution radius, *r*. The value of *r* should be zero at the top of the crown, should increase along crown until it reaches a maximum (r_{max}), and then decreases to the base of the live crown (r_b) where live branches still bear foliage. Note that the Maxima function (Keen and Spain 1992) can be used to represent foliage distribution within the crown well and its mathematical expression is:

$$r = \alpha h e^{-\beta h} \tag{1}$$

where h (m) is crown depth, and α and β are parameters.

The value of a unit virtual rotator of foliage biomass (unit length *dh*, m) in the cross sectional panel of the live crown can be obtained using the cylinder volume equation, $\pi r^2 dh$, and whole tree foliage biomass can be expressed with the following integration:

$$F_B = \int_0^l k r^2 dh = \int_0^l k(\alpha h e^{-\beta h})^2 dh = \int_0^l k\alpha^2 h^2 e^{-\gamma h} dh \tag{2}$$

where F_B is foliage biomass (kg), *l* crown length (m), $\gamma = 2\beta$, and *k* the transition coefficient.

The function under integration [on the utmost right hand side of equation (2)] is a Gamma distribution function with location parameter 0 (zero), power parameter 3, and exponential parameter $1/\gamma$ (Hogg and Craig 1995, p.132). The symbolic solution of equation (2) is:

$$F_B = \frac{k\alpha^2}{\gamma^3}(2 - \gamma^2 l^2 e^{-\gamma l} - 2\gamma l e^{-\gamma l} - 2e^{-\gamma l}) \tag{3}$$

which is equivalent to:

$$F_B = \frac{k\alpha^2}{\gamma^3}[2(1 - e^{-\gamma l}) - \gamma l(\gamma l + 2)e^{-\gamma l}] \tag{4}$$

According to the pipe model theory, foliage biomass can be estimated using the sapwood area at the base of the live crown. Kinerson and others (1974), Waring and others (1982), and Valentine and others (1994) pointed out that dry foliage biomass is highly correlated to the cross-sectional area at the base of the live crown (crown basal area), which can serve as a surrogate to the sapwood area.

We used analysis of covariance to detect impacts of cultural treatments on foliage biomass with d.o.b. or diameter at breast height (d.b.h., cm) as one of covariates where the most responsive factor was complete vegetation control for trees in the Piedmont, and fertilization for trees in the Lower Coastal Plain. When d.b.h. is used as a covariate, fertilization (F) is a significant factor (in the Lower Coastal Plain) and complete competing vegetation control (H) is not (in the Piedmont); when d.o.b. is a covariate, neither F nor H is a significant factor. The above analysis indicates that treatment impacts could be ignored during parameter estimation if d.o.b. is used as a predictor, which simplifies model structure and parameter estimation. Thus, d.o.b. rather than d.b.h. was used as a predictor of foliage biomass.

Our data also showed that unit foliage biomass (total tree foliage biomass divided by crown basal area) increased with crown height, C_h (m). It is also true that crown height is linearly related to tree age. Thus, crown height was chosen as a predictor of foliage biomass.

Reformulating equation (4) using d.o.b. and C_h to replace the coefficient *k*, a foliage biomass prediction model is obtained as:

$$F_B = \frac{\eta dob^{\beta} C_h^{\tau} \alpha^2}{\gamma^3}[2(1 - e^{-\gamma l}) - \gamma l(\gamma l + 2)e^{-\gamma l}]. \tag{5}$$

Re-parameterizing equation (5), the model can be written as:

$$F_B = \xi dob^{\beta} C_h^{\tau}[2(1 - e^{-\gamma l}) - \gamma l(\gamma l + 2)e^{-\gamma l}] \tag{6}$$

where ξ is a parameter and the others as defined as above.

We found a strong linear relationship between foliage biomass and branch biomass, which agrees with the description from Causton (1985). According to this discovery, we proposed a prediction model form for branch biomass (B_B, kg):

$$B_B = \zeta F_B \tag{7}$$

where ζ is the proportionality coefficient.

PARAMETER ESTIMATION

Foliage biomass prediction equation (6) is intrinsically nonlinear and needs to be fit using a nonlinear modeling technique. During parameter estimation, the mixed-effects modeling approach was chosen to obtain consistent and unbiased estimates. This approach has the capability to detect the impact of site on foliage biomass, which is usually considered a random impact due to the uncertainty of actions and interactions from external forces. Note that FB is an endogenous variable because it is the dependent variable in equation (6) and the independent variable in equation (7) (Borders and Bailey, 1986). To eliminate simultaneous equation bias, observed FB values were replaced with predicted values during fitting the branch biomass prediction equation. A joint model-fitting method, which addresses all dependent variables (FB and BB) simultaneously, was employed, and all dependent variables were stored in a one-column matrix (vector). With the use of an indicator (dummy) variable, the dependent variable matrix on the left-hand side is functionally related to the independent variable matrix on the right-hand side. This approach

is similar to that introduced by Zhang and others (2002). Apiolaza and Garrick (2001) have also used a similar fitting approach.

In mixed-effects modeling terminology, subject denotes the entity with stipulated character. Data obtained from the same subject may exhibit correlation with each other, and it is defined as the within-subject correlation. There may also be relationships among different subjects that are defined as the among-subject correlation. To allow for correlation within subjects using the SAS nonlinear mixed-effects modeling algorithm, the repeated (RTYPE) option in a SAS macro for nonlinear mixed-effects modeling (Littell and others 1996) was evoked. Among-subject correlation can be modeled by invoking the option, RANDOM. Suspecting impacts from varying drainage and fertility conditions, or soil types for the sites involved, we adopted site as the subject with a total number of four sites (two in each region).

RESULTS

Impacts of cultural treatments on foliage biomass can be ignored during parameter estimation if d.o.b. is used as a predictor. It was also found that the slope parameters (ξ and ζ) are not significantly different (statistically) by region. Thus, both foliage and branch biomass models were fit using the same slope parameters for two regions (the PID and the LCP), and all estimates of parameters were found to be statistically significant (table 1). The estimates of random parameter (u) for the four sites show that site impacts in both regions are significantly different and cannot be ignored. Overall, the models fit our data well (table 2).

Residual analysis was done to evaluate the fit quality, and no obvious trends of the residual distribution were found.

Table 2—Fit statistics of the foliage and branch biomass prediction equations obtained using mixed-effects approach and statistics for goodness of fit

Fit statistics of mixed-effects fitting:	
-2 Res Log Likelihood	1904.5
AIC (smaller is better)	1910.5
BIC (smaller is better)	1908.6

Goodness of fit:

	SEE	*BIAS*	*ABIAS*
		kg/tree	
F_B	0.5976	0.0322	0.4830
B_B	1.3202	0.0229	1.1164

-2 Res Log Likelihood = the -2 Restricted Log Likelihood value; F_B = foliage biomass; B_B = branch biomass; SEE = standard error of estimate; BIAS = average bias; and ABIAS = absolute average bias.

Source: Littell and others 1996, pp. 139, 403-404), AIC the Akaike Information Criterion (Pinheiro and Betes 2000, pp. 10; BIC the Bayesian Information Criterion (Pinheiro and Betes 2000, pp. 10).

Validation of these prediction equations was not carried out directly because suitable independent data are not available. However, needle data collected from litter traps provided a pseudo set of validation data. Table 3 lists average foliage biomass on a tree basis for fertilized stands and unfertilized stands with all age classes in both regions for model

Table 1—Estimates obtained for foliage and branch biomass prediction models, where STD is the standard error, LCL and UCL the lower and upper 95 percent confidence limits

Parameter	Estimate	STD	LCL	UCL
Fixed				
$\hat{\xi}$	1.8290E-2	2.8000E-4	1.7740E-2	1.8840E-2
$\hat{\beta}$	1.7618	0.0628	1.6385	1.8851
$\hat{\gamma}$	1.3100	0.1572	1.0017	1.6188
$\hat{\tau}$	0.1116	0.0109	0.0901	0.1330
$\hat{\zeta}$	2.4269	0.0394	2.3496	2.5042
Random	**Estimate**	**STD**	**t-value**	**Pr > |t|**
$\hat{u}_1$	-0.1281	0.0374	-3.43	0.0006
$\hat{u}_2$	-0.0471	0.0406	-1.16	0.2465
$\hat{u}_3$	-0.1847	0.0646	-2.86	0.0044
$\hat{u}_4$	0.1909	0.0666	2.87	0.0043

Table 3—Comparisons of average predicted foliage biomass of a tree [F_B (kg)], average foliage biomass of a tree from destructive samples (DF_B, and litter trap collected foliage biomass of a tree [TFB_B (kg)] for most responded cultural treatments by age in both PID and LCP installations

		Litter trap prediction		Destructive sampled
	Age	TFB	FB	DFB
	yr.	- - - - - - - - *kg/tree* - - - - - - - -		
PID				
No H	5	1.44	1.04	1.15
	10	2.23	2.91	3.27
	12	4.10	3.42	3.48
H	5	1.38	2.36	2.54
	10	1.96	3.70	4.09
	12	2.68	3.85	4.05
LCP				
No F	6	3.08	3.08	2.98
	10	2.72	3.40	3.07
	12	2.56	3.41	3.10
F	6	3.33	3.25	3.06
	10	3.86	4.10	3.85

H = complete vegetation control; F = fertilization.

predictions (F_B, kg), litter trap collections (TF_B, kg), and destructively sampled data (DF_B, kg). The results showed that the difference between F_B and TF_B is somewhat larger than that between TF_B and DF_B. The larger difference may be due to the difference of collection times for litter trap data and destructively sampled data, collection methods, calculations and estimation methods, or impacts from other unobservable factors.

DISCUSSION

We derived a foliage biomass prediction model based on the Gamma distribution that can predict both total tree foliage biomass and the foliage biomass for any segment of the crown. This capability can improve estimates of tree and stand carbon gain, which is known to vary with foliage biomass as well as foliage position within crowns. The functional relationship between foliage biomass and diameter outside bark at the base of the live crown has been constructed according to the pipe model theory. Valentine and others (1994) suggested using a 'taper-based surrogate' consisting of a 'live crown ratio above breast height' that is the ratio of crown length to the distance between breast height and the top of tree, and d.b.h. squared to predict foliage biomass. Based on the same theory, Naidu and others (1998) employed d.b.h. as a predictor of foliage biomass. From our data, it was found the diameter at the base of the live crown was a better predictor of foliage biomass than d.b.h. or the surrogate suggested by Valentine and others (1994). However, if d.o.b. is not available via direct measurement it can be estimated indirectly using taper function and crown height. This estimate of d.o.b. then corresponds to the surrogate suggested by Valentine and others (1994).

We found that cultural treatments have significant impacts on foliage biomass growth. For instance, trees from complete vegetation control stands produced more foliage biomass than control or fertilized stands in the Piedmont, whereas fertilized trees produced the most foliage biomass in the Lower Coastal Plain. Also an interaction was found between age and the fertilization treatment in the Piedmont, which shows that the fertilized trees produced more foliage biomass than unfertilized trees at age 10 and above, but not at age 5 (Will and others 2002). The confounding between age and treatment complicates parameter estimation and even model structure. On the other hand, d.o.b. is a more robust predictor and is closely related to current crown status regardless of cultural treatment. Conversely, our analysis showed that the impacts of cultural treatments must be considered explicitly during parameter estimation if d.b.h. is used as a predictor.

A close linear relationship between foliage and branch biomass was described previously (Causton 1985) and confirmed by our data. Using a proportionality constant, branch biomass can be easily estimated using the prediction of foliage biomass, which significantly simplifies the structure of branch biomass prediction model.

We did not have a truly independent set of data with which to validate our models. However, we had estimates of foliage biomass that were obtained from litter trap data. In most instances, there was good agreement between the two estimates. In a few instances, however, we did find large differences between model predictions and litter trap data. The errors may be from different collection methods or seasonal variation between collection times.

Clearly, the model derived and presented above fits our crown data well. It should be emphasized that this model is not a purely statistical model but has a solid basis in the physical nature of tree crowns and is supported with the pipe model theory. Consequently, this model predicts foliage and branch biomass for various cultural treatments using dendrometric variables from individual trees that reflect crown differences by cultural treatment. This makes the model relatively general in that it is not necessary to parameterize separately by cultural treatment. For model application, one needs to measure diameter outside bark at the base of the live crown (d.o.b.), crown height, and total height. As a substitute, d.o.b. value can be predicted using stem taper function and predictors—d.b.h., total height, and crown height.

ACKNOWLEDGMENTS

Authors wish to gratefully acknowledge the sponsors of the Consortium for Accelerated Pine Production Studies: Boise Cascade, Champion International, Gilman Paper Co., International Paper Co., Jefferson Smurfit, Mead Coated Board, Rayonier Inc., Temple-Inland, The Timber Company, Weyerhaeuser Co., UBS Timber Investors, Union Camp Corp., U.S. Alliance, the U.S. Department of Energy, and The D.B. Warnell School of Forest Resources at the University of Georgia.

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VISUAL BASIC GROWTH-AND-YIELD MODELS WITH A MERCHANDISING OPTIMIZER FOR PLANTED SLASH AND LOBLOLLY PINE IN THE WEST GULF REGION

R.L. Busby, S.J. Chang, P.R. Pasala, and J.C.G. Goelz[1]

Abstract—We developed two growth-and-yield models for thinned and unthinned plantations of slash pine (*Pinus elliottii* Engelm. var *elliottii*) and loblolly pine (*P. taeda* L.). The models, VB Merch-Slash and VB Merch-Lob, can be used to forecast product volumes and stand values for stands partitioned into 1-inch diameter-at-breast-height classes at any stage of plantation development from ages 10 through 50. Variables required to run the programs are age, density, site quality, minimum and maximum dimensions of products, and product prices. A merchandising optimizer converts predicted stand tables into an estimated optimum product mix by using a dynamic programming algorithm that maximizes the stand's selling value. The programs are written in Visual Basic and are available from the authors.

INTRODUCTION

The Nation's demand for timber products has been growing, increasing the pressure to harvest pine stands in the South. As a result, landowners increasingly are investing in pine plantation management. Because establishment and management of plantation pine stands are major investments, landowners need to have a sense of the value of future harvests if they are to justify their investments. Two computer models, VB Merch-Slash and VB Merch-Lob, allow landowners to model the development of slash pine (*Pinus elliottii* Engelm. var. *elliottii*) and loblolly pine (*P. taeda* L.) plantations. The models provide information on product mix and harvest value of both thinned and unthinned pine plantation harvests.

PROGRAM DESCRIPTION

VB Merch-Slash builds upon a planted slash pine growth-and-yield model (Zarnoch and others 1991). A computer program for this system, called COMPUTE_P-SLASH, was released (Baldwin and Ferguson 2003). The growth-and-yield subroutines are based on measurement data taken from study plots in unthinned and thinned slash pine plantations in the South's west gulf region. The data pool was composed of 543 thinned-stand growth-period observations on 0.10- to 0.25-acre plots. Generally, the growth period was 5 years but ranged from 3 to 11 years. The plots were not located in areas where survival was poor or where heavy damage from insects, disease, or other agents was present. For the most part, thinning was from below, but at later ages a good distribution of tree diameters across the plot was also a criterion. In addition, there were 530 residual-stand observations of postthinning conditions (Zarnoch and others 1991). VB Merch-Slash adds merchandising routines that divide up the stand-stock table of the model into product classes, which allow calculation of total stand value and total stand volume by product classes. VB Merch-Slash is written in Visual Basic, which allows for easy input and output.

VB Merch-Lob is an updated version of COMPUTE_MERCHLOB (Busby and others 1990). The growth-and-yield calculations are based on measurement data taken from study plots in unthinned and thinned loblolly plantations located in east Texas, north and central Louisiana, and eastern Mississippi. Plot age (from the time of planting) ranged from 10 through 45 years, site index (base age 25) from 40 to 90 feet, and initial planting density from 109 to 2,700 trees per acre. The thinning interval for stands in the long-term studies was 5 years, and residual densities after thinning ranged from 50 to 130 square feet of basal area per acre. The program is also written in Visual Basic, rather than the original Fortran, making it more flexible and user-friendly.

Both VB Merch-Slash and VB Merch-Lob can be used to forecast product volume and stand values for stands partitioned into 1-inch diameter-at-breast-height classes at any stage of plantation development from ages 10 through 50. The minimum initial variables required to run the program are age, density, site quality, minimum and maximum dimensions of products, and product prices. The merchandising optimizer converts predicted stand tables into an estimated optimum product mix by using a dynamic programming algorithm that maximizes the selling value of the stand.

Six different products can be specified: poles, veneer bolts, saw logs, chip-n-saw logs, pulpwood bolts, and chips. Residual wood is an additional product to account for any available wood in the bole of the tree not accounted for in the other six products. The model allocated the entire bole of each tree to one or more of the six product categories or to residual wood. The units of measurement for products are cords, tons, and board feet (in Doyle, Scribner, or International 1/4-inch rule), which can be set for each product.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Product dimensions are the minimum and maximum top-end diameters, minimum and maximum piece length, piece-length increment, and an allowance for trim. For example, the user can say that poles must have a top-end diameter between 4 and 10 inches and be between 40 and 70 feet in length. Unit prices by product also must be specified. The user specifies an array of possible product sizes, and the model calculates the optimal cutting pattern to maximize the harvest value of the stand.

Two problems arise when attempting to estimate the best product mix based upon information given in the growth-and-yield model: (1) form and disease product defect information are not provided, and (2) small quantities of high-value products may be too expensive to sort out and sell. Poor form and disease are modeled by including a variable that allows the user to specify the percentage of properly sized trees from which a particular product cannot be made. For example, not all trees 40 feet tall to a 6-inch top are suitable for pole production, because some may have poor form or some defect that precludes the use of that log as a pole. If 60 percent of all properly sized trees have defects, then the variable would be set to 60 percent. The second problem that of small quantities of high-value products being too expensive to sort and sell is solved by inclusion of a minimum harvest variable. The user sets the minimum harvest volume required in a stand to make production economically viable. For example, the user may specify that a minimum of 1,000 board feet per acre of sawtimber logs must be produced if sawtimber is to be produced at all.

VB Merch-Lob and VB Merch-Slash provide two tables of output, a product-yield table with the specified product possibilities and a value table providing dollar amounts for the products. These tables represent the highest-value solutions, subject to constraints imposed by users. The information then can be used to make decisions critical to managing plantation loblolly and pine plantations.

DISCUSSION AND CONCLUSION

The Nation's demand for timber production is growing, and landowners are increasingly investing in southern pine plantations to meet the demand. Plantations must be profitable to landowners if required investments are going to be made. We offer the VB Merch-Slash and VB Merch-Lob models to help landowners make good investment decisions by providing estimates of harvest values of thinned and unthinned slash and loblolly pine stands. Landowners can predict the economic return of management options, using these models to develop harvest values and make better informed decisions about their plantation investments.

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ANNUAL TREE GROWTH PREDICTIONS FROM PERIODIC MEASUREMENTS

Quang V. Cao[1]

Abstract—Data from annual measurements of a loblolly pine (*Pinus taeda* L.) plantation were available for this study. Regression techniques were employed to model annual changes of individual trees in terms of diameters, heights, and survival probabilities. Subsets of the data that include measurements every 2, 3, 4, 5, and 6 years were used to fit the same tree-growth equations. Two methods of estimating parameters of the annual growth equation from periodic measurements were evaluated. The Constant Rate method assumed a constant tree-survival probability and constant diameter and height-growth rates during the growing interval. In contrast, these annual changes were assumed to be different from year to year in the Variable Rate method. Results indicated that the Variable Rate method out performed the Constant Rate method in predicting annual tree growth from periodic measurements.

INTRODUCTION

A distance-independent individual tree model consists of three main components: tree diameter and height-growth equations and a tree survival function. Equations have been developed to predict tree diameter growth (Amateis and others 1989, Belcher and others 1982, Lessard and others 2001, Mabvurira and Miina 2002, Zhang and others 1997) and height growth (Courbaud and others 1993, Golser and Hasenauer 1997, Lynch and Murphy 1995, Ritchie and Hann 1986). Logistic functions have generally been used in modeling the probability that a tree survives a growing period (Buchman 1979, 1983; Hamilton 1974; Hamilton and Edwards 1976; Monserud 1976; Monserud and Sterba 1999; Zhang and others 1997).

Predicting annual tree growth and survival is not an easy task because trees are not measured every year but often at some interval. McDill and Amateis (1993) developed two interpolation methods for modeling annual growth of one variable (e.g., tree height). One of their methods was later generalized by Cao and others (2002) for predicting many variables (e.g., tree diameter, height, and crown ratio). These interpolation methods were shown to perform better than the Constant Rate method, which assumes a constant growth rate for the entire period. It is particularly difficult to predict annual tree survival from periodic measurements because if a tree was found dead at the end of a period, there was no record of when that actually happened. The survival probability is often assumed to remain constant during the growing period (Hamilton and Edwards 1976, Monserud 1976). Cao (2000) developed an iterative method to account for variable rates of annual survival and diameter growth. The method was later modified to include annual height growth (Cao 2002). The objective of this study is to evaluate the Constant Rate method versus Cao's (2002) Variable Rate method in estimating parameters of an individual tree model that consists of annual tree survival, diameter growth, and height-growth equations.

DATA

Data from two plots in an unthinned loblolly pine (*Pinus taeda* L.) plantation were made available for this study by Dr. Paul Y. Burns, Professor Emeritus of the School of Renewable Natural Resources, Louisiana State University. This plantation was in the School's Lee Memorial Forest, near Bogalusa, LA. There was originally a total of 171 trees per plot planted in a 9-foot by 12-foot spacing, resulting in a plot size of 0.424 acres. Diameter at breast height (d.b.h.), total height, and survival status (dead or alive) of these trees were recorded annually from age 2 to age 21 (fig. 1). Subsets of the above data were created to include measurements every 2, 3, 4, 5, and 6 years.

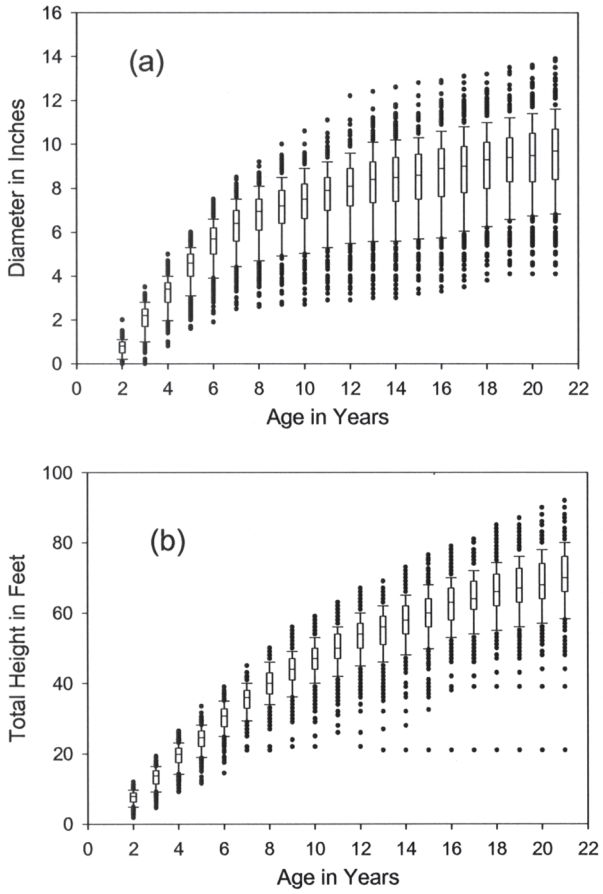

Figure 1—Box plots of tree d.b.h. (a) and total height (b) measured over time.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

METHODS

The following individual tree model comprised of equations predicting annual survival, and diameter and height growth was selected after preliminary analyses:

$$d_{i,\,t+1} - d_{i,\,t} = \alpha_1 B_t^{\alpha_2} H_t^{\alpha_3} h_{i,\,t}^{\alpha_4} \exp(\alpha_5 d_{i,\,t}/D_{q,\,t}) + \varepsilon_{i,\,t} \quad (1.a)$$

$$h_{i,\,t+1} - h_{i,\,t} = \beta_1 A_t^{\beta_2} B_t^{\beta_3} H_t^{\beta_4} h_{i,\,t}^{\beta_5} \exp(\beta_6 d_{i,\,t}/D_{q,\,t}) + \varepsilon_{i,\,t} \quad (1.b)$$

$$p_{i,\,t+1} = [1 + \exp(\gamma_1 B_t + \gamma_2 H_t + \gamma_3 h_{i,\,t})]^{-1} \quad (1.c)$$

where

$d_{i,\,t}$ and $h_{i,\,t}$ = d.b.h. in inches and total height in feet, respectively, of tree i at age A_t,

$p_{i,\,t+1}$ = probability that tree i survived the period from age A_t to A_{t+1},

H_t = dominant height (average height of the dominants and codominant heights) in feet at age A_t,

B_t = stand basal area in square feet per acre at age A_t,

$D_{q,\,t}$ = quadratic mean diameter in inches at age A_t, and

$\varepsilon_{i,\,t}$ = error term.

Two methods for estimating parameters of the above tree model, the Constant Rate method and the Variable Rate method, will be discussed as follows:

Constant Rate Method

In this method, the growth rates of diameter and height of each tree were assumed to be constant during the growth period from age A_t to A_{t+q}, where q is the length of the period. Similarly, the survival probability was also considered constant during this period. Equations (1.a – 1.c) are rewritten as follows:

$$(d_{i,\,t+q} - d_{i,\,t})/q = \alpha_1 B_t^{\alpha_2} H_t^{\alpha_3} h_{i,\,t}^{\alpha_4} \exp(\alpha_5 d_{i,\,t}/D_{q,\,t}) + \varepsilon_{i,\,t} \quad (2.a)$$

$$(h_{i,\,t+q} - h_{i,\,t})/q = \beta_1 A_t^{\beta_2} B_t^{\beta_3} H_t^{\beta_4} h_{i,\,t}^{\beta_5} \exp(\beta_6 d_{i,\,t}/D_{q,\,t}) + \varepsilon_{i,\,t} \quad (2.b)$$

$$p_i = [1 + \exp(\gamma_1 B_t + \gamma_2 H_t + \gamma_3 h_{i,\,t})]^{-q} \quad (2.c)$$

where p_i is the probability that tree i survived the period from age A_t to A_{t+q}.

A method suggested by Borders (1989) was used to simultaneously estimate parameters of the diameter and height-growth equations; this fitting procedure involved the use of option SUR (seemingly unrelated regression) of SAS procedure MODEL (SAS Institute Inc. 1993). Maximum likelihood estimation of parameters of the survival equation was obtained using weighted nonlinear regression (Walker and Duncan 1967).

Variable Rate Method

This method allowed the survival and growth rates to vary from year to year as functions of constantly changing stand variables and tree variables. Annual changes in diameter, height, and survival probability were modeled in a recursive manner as follows:

Year (t+1)

$$\hat{d}_{i,t+1} = d_{i,\,t} + \alpha_1 B_t^{\alpha_2} H_t^{\alpha_3} h_{i,\,t}^{\alpha_4} \exp(\alpha_5 d_{i,\,t}/D_{q,\,t}) \quad (3.a.1)$$

$$\hat{h}_{i,t+1} = h_{i,\,t} + \beta_1 A_t^{\beta_2} B_t^{\beta_3} H_t^{\beta_4} h_{i,\,t}^{\beta_5} \exp(\beta_6 d_{i,\,t}/D_{q,\,t}) \quad (3.b.1)$$

$$p_{i,\,t+1} = [1 + \exp(\gamma_1 B_t + \gamma_2 H_t + \gamma_3 h_{i,\,t})]^{-1} \quad (3.c.1)$$

Year (t+2)

$$\hat{d}_{i,t+2} = \hat{d}_{i,t+1} + \alpha_1 \hat{B}_{t+1}^{\alpha_2} \hat{H}_{t+1}^{\alpha_3} \hat{h}_{i,t+1}^{\alpha_4} \exp(\alpha_5 \hat{d}_{i,t+1}/\hat{D}_{q,t+1}) \quad (3.a.2)$$

$$\hat{h}_{i,t+2} = \hat{h}_{i,t+1} + \beta_1 A_t^{\beta_2} \hat{B}_{t+1}^{\beta_3} \hat{H}_{t+1}^{\beta_4} \hat{h}_{i,t+1}^{\beta_5} \exp(\beta_6 \hat{d}_{i,t+1}/\hat{D}_{q,t+1}) \quad (3.b.2)$$

$$p_{i,\,t+2} = [1 + \exp(\gamma_1 \hat{B}_{t+1} + \gamma_2 \hat{H}_{t+1} + \gamma_3 \hat{h}_{i,t+1})]^{-1} \quad (3.c.2)$$

Year (t+q)

$$d_{i,\,t+q} = \hat{d}_{i,t+q-1} + \alpha_1 \hat{B}_{t+q-1}^{\alpha_2} \hat{H}_{t+q-1}^{\alpha_3} \hat{h}_{i,t+q-1}^{\alpha_4} \exp(\alpha_5 \hat{d}_{i,t+q-1}/\hat{D}_{q,t+q-1}) + \varepsilon_i \quad (3.a.q)$$

$$h_{i,\,t+q} = \hat{h}_{i,t+q-1} + \beta_1 A_t^{\beta_2} \hat{B}_{t+q-1}^{\beta_3} \hat{H}_{t+q-1}^{\beta_4} \hat{h}_{i,t+q-1}^{\beta_5} \exp(\beta_6 \hat{d}_{i,t+q-1}/\hat{D}_{q,t+q-1}) + \varepsilon_i \quad (3.b.q)$$

$$p_{i,\,t+q} = [1 + \exp(\gamma_1 \hat{B}_{t+q-1} + \gamma_2 \hat{H}_{t+q-1} + \gamma_3 \hat{h}_{i,t+q-1})]^{-1} \quad (3.c.q)$$

where the stand-level variables were predicted from the following equations:

$$\hat{H}_{t+s+1} = \exp\{\lambda_1 + [\ln(\hat{H}_{t+s}) - \lambda_1](A_{t+s}/A_{t+s+1})\} \quad (4.a)$$

$$\ln(\hat{B}_{t+s+1}) = \ln(\hat{B}_{t+s}) + \tau_1 (1/A_{t+s} - 1/A_{t+s+1}) + \tau_2 [\ln(\hat{H}_{t+s+1}) - \ln(\hat{H}_{t+s})] \quad (4.b)$$

$$\ln(\hat{D}_{q,t+s-1}) = \ln(\hat{D}_{q,t+s}) + \delta_1 (1/A_{t+s} - 1/A_{t+s+1}) + \delta_2 [\ln(\hat{H}_{t+s+1}) - \ln(\hat{H}_{t+s})] \quad (4.c)$$

and the probability that tree i survived the period from age A_t to A_{t+q} is given by

$$p_i = \prod_{s=1}^{q} p_{i,t+s} \quad (5)$$

RESULTS AND DISCUSSION

Tree growth (based on data taken at intervals ranging from 1 to 6 years) was projected for a tree measuring 0.7 inches in d.b.h. and 7 feet in total height at age 2. Initial stand variables at age 2 were:

Dominant height = 8 feet

Stand basal area = 1.5 square feet per acre

Quadratic mean diameter = 0.8 inches.

Figure 2a shows that the Constant Rate method underestimated tree-diameter growth. The linear interpolation technique employed by this method always resulted in lower estimates of annual growth. The longer the interval between two measurements, the lower the diameter growth projection curve. Data taken at 6-year intervals yielded a diameter-growth curve that was consistently lower by almost 4 inches between age 11 and age 21.

On the other hand, the Variable Rate method yielded diameter-growth curves that were very close for all interval lengths (fig. 2b). This method produced better predictions for annual diameter growth because it used the model to make interpolations. Curves from 1-year and 6-year intervals were at most 1 inch apart and were less than 0.5 inches different beyond age 11.

Figures 3a and 3b tell a similar story for total height-growth projections. The Constant Rate method produced lower height-growth curves when based on data that were collected at longer intervals (fig. 3a). The curve fitted from height measurements at every 6 years was more than 15 feet lower at age 17 and beyond. Figure 3b shows that height-growth curves constructed using the Variable Rate method were virtually indistinguishable regardless of interval length.

The Variable Rate method also outperformed the Constant Rate method in predicting tree survival probability (figs. 4a and 4b). Modeling the annual probability of tree survival is always a challenge because one never knows exactly when the tree died during the period. Although the tree-survival curves from various interval lengths assumed various shapes, the differences were much less pronounced for the Variable Rate method (maximum difference = 0.10) than for the Constant Rate method (maximum difference = 0.35).

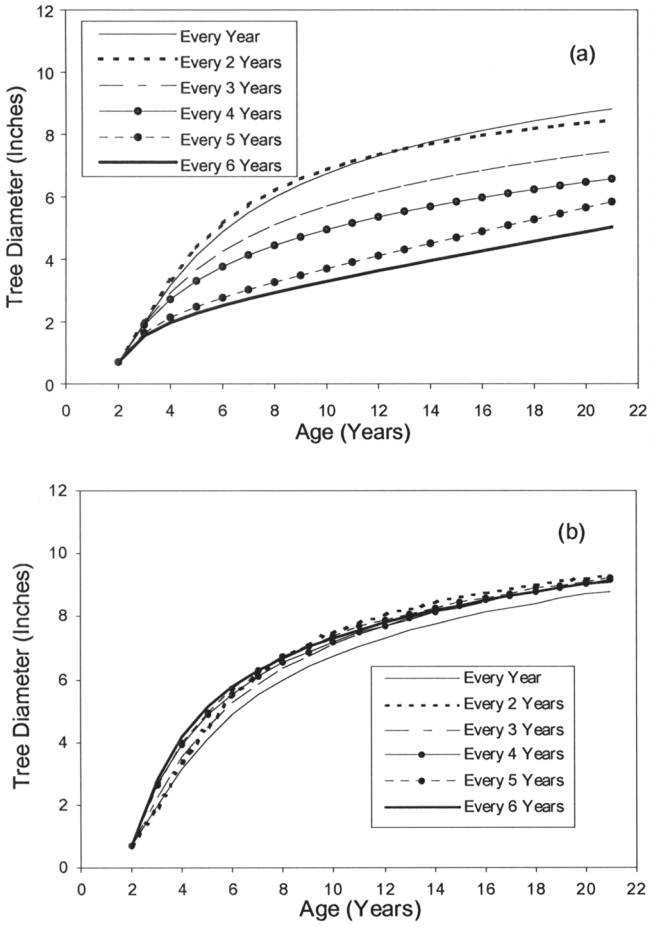

Figure 2—Projections of tree diameter over time based on measurements taken at different intervals. Parameters of the diameter-growth equation were obtained from (a) the Constant Rate method and (b) the Variable Rate method.

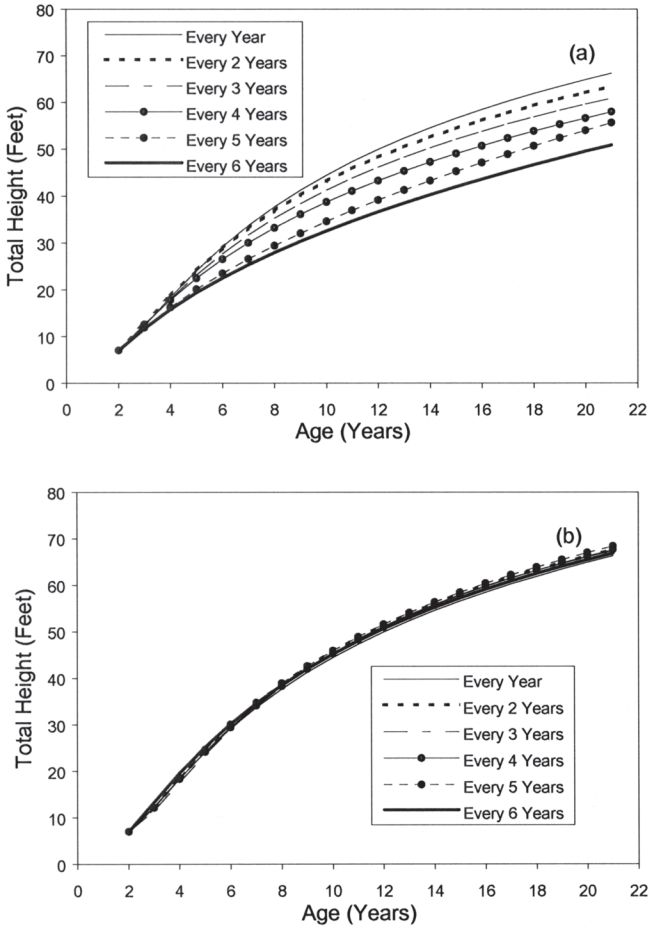

Figure 3—Projections of tree total height over time based on measurements taken at different intervals. Parameters of the height-growth equation were obtained from (a) the Constant Rate method and (b) the Variable rate method.

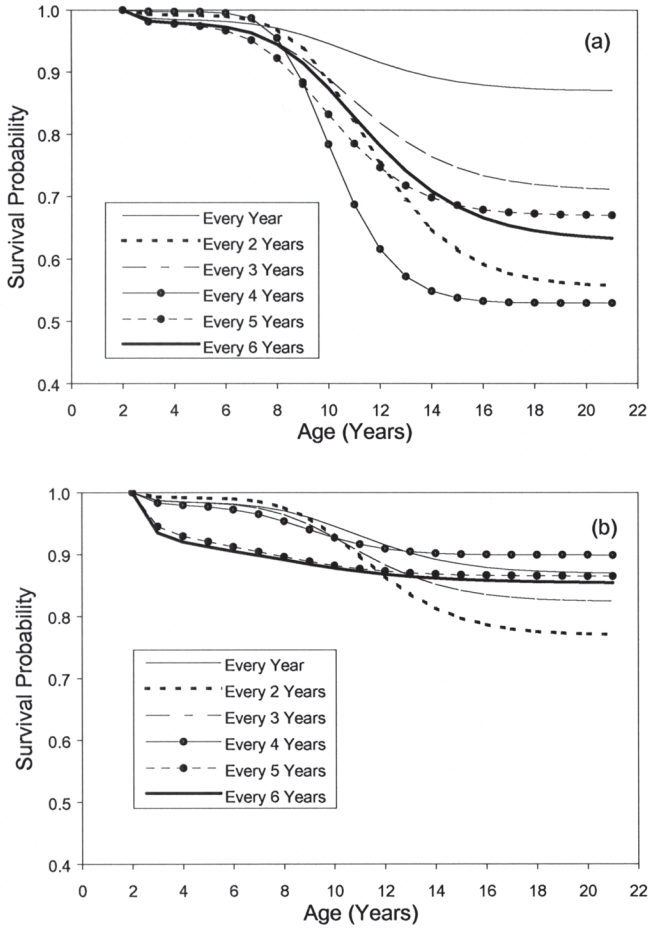

Figure 4—Projections of tree survival probability over time based on measurements taken at different intervals. Parameters of the tree-survival equation were obtained from (a) the Constant Rate method and (b) the Variable rate method.

Because tree and stand variables keep changing every year, a method such as the Variable Rate method that allows diameter growth, height growth, and tree survival probability to vary annually should perform well. This method should be superior to the Constant Rate approach, as clearly demonstrated in this study. Results also indicated that annual tree growth and survival could be successfully modeled using data measured up to 6 years apart. Even though a loblolly pine data set was used in this study, the Variable Rate approach should be applicable to other species as well.

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RELATION OF STEM DIAMETER, BRANCH BASAL AREA, AND LEAF BIOMASS IN RAPIDLY GROWING LOBLOLLY PINE

Thomas M. Williams and Charles A Gresham[1]

Abstract—Twenty loblolly pines, growing in International Paper's maximum growth experiment at Bainbridge GA, were destructively sampled at the end of the sixth growing season. Ten trees in the control and 10 in the maximum treatment were sampled. All trees were planted at a 2.4- by 3.6-m spacing and grown with complete competition control. The maximum trees also received irrigation, fertilization, and pest control. Tree measures were basal diameter, d.b.h., height of live crown, diameter at base of live crown, and total height. Each tree was sectioned at 1-m intervals and stem diameter determined at each end. Branches were removed and height, basal diameter, and length were measured on each branch. Branches were separated into foliated and unfoliated segments and weighed green. One branch from each meter was returned to the lab to determine dry weight and foliated branch to foliage ratios. The maximum treatment trees were considerably larger (17.2 cm- d.b.h., 9.57 m tall, 0.118 m^3 stem volume to 5-cm top) than the controls (13.5 cm- d.b.h., 7.72 m tall, 0.58 m^3 stem volume), but crown lengths were similar (6.7 m maximum, 6.6 m control). In the upper 5 m of crown, leaf biomass was highly correlated with branch basal area (r^2 = 0.697 to 0.947), and there was a constant ratio of leaf biomass to branch basal area (50.4gm per cm^2 for maximum, 50.2 gm per cm^2 for control). In general, we found a constant ratio of bole basal area to cumulative branch basal area throughout the crowns (0.94 for controls, 1.06 for maximum).

INTRODUCTION

Growth and productivity of loblolly pine (*Pinus taeda* L.) have been studied for several decades. There has been a series of principles that have been formulated to explain growth of forest trees. Carl Olaf Tamm proposed that conifer growth in Sweden was controlled by the supply rate of nitrogen. Ågren (1983) presented a formal differential equation suggesting the instantaneous growth rate was determined by the soil supply rate of nitrogen. The equation was found to be accurate for small seedlings and foliage (Ågren 1985). Vose and Allen (1988) tied foliage production to stem wood volume, showing that subsequent stand growth is highly correlated to present leaf area index. Waring and others (1982) found a predictable relation between sapwood basal area and foliar biomass, suggesting wide applicability of the pipe model of Shinozaki and others (1964). The pipe model described a tree as a collection of pipes that conduct water from roots to leaves. New foliage requires a simultaneous increase in branch, bole, and root cross section to carry water to the new foliage.

Branches are the connection of stem and foliage. Spurgel and others (1991) examined literature on the degree of branch autonomy. They concluded that older branches are essentially autonomous with regard to carbon. That is, if respiration exceeds photosynthesis in an older branch, it does not import photosynthate from the stem. They generally found that this was true for old branches and, with respect to carbon, older branches were completely autonomous. If respiration exceeded photosynthesis over a sustained period, older branches died rather than withdraw carbon from the stem. Their conclusions on water tended to support the pipe model in that individual branches were hydraulically separated, and stress on one branch was not transmitted to others.

In addition to providing conductive material, the stem also provides support for the tree. Long and others (1981) examined form of 45-year-old Douglas fir [*Pseudotsuga menziesii* (Mirb.)Franco] and found that stem form fit the cubic equation first proposed by Metzger (1893). He estimated bole diameter distribution required to produce uniform resistance to wind acting on the crown. They found that the cubic power equation of Metzger could explain the stem form of Douglas-fir.

In this paper we will examine growth and tree morphology of loblolly pine grown with only light, temperature, and intra-specific competition limitation. These trees are part of an International Paper study at Bainbridge, GA, on which there have been several previous reports (Gresham and Williams 2002, McLemore and others 1999, Samuelson 1998, Williams 1999, Williams and Gresham 2002). We compared loblolly pine grown in the most and least intensive treatments after six growing seasons. Growth and morphology were examined in relation to the above principles.

METHODS

The study is located on International Paper's Silver Lake Farm, Southlands Experimental Forest in Bainbridge, GA (30°51´ N, 80°45´ W). The study examines addition of irrigation, fertilization with irrigation (fertigation), and pest control to superior loblolly that were planted on an abandoned agricultural field and that have been maintained competition free. Trees were planted in the spring of 1995 on 12-foot subsoiled rows on a 10-foot spacing within rows. Design was randomized complete block with three reps of four treatments. Plots were 144 feet by 180 feet or 12 rows and 18 trees per row. The inner 8 rows and 10 trees were used as a measurement plot. In addition to the three measurement replications, a destructive sampling partial

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

replication was planted with only maximum and minimum treatments.

In late February 2002, we sampled 10 trees from each maximum and minimum treatment. Trees were systematically sampled from the destructive replication to assure that each sampled tree would have four surrounding trees at the same spacing as trees on the measurement replications. Trees were cut at ground line and measures of basal diameter, d.b.h., height and diameter at base of live crown, and total height were taken. Each tree was then cut into 1-m sections. Diameter at each end of the meter was recorded, total green weight determined, and a disk removed and weighed green and dry. Dead branches were combined and weighed green and a sub sample weighed dry. Each branch was removed, and height along stem, basal diameter, and length were measured. Foliated and unfoliated sections were separated and weighed green. One branch per m was returned to the laboratory. The dried foliated branch and needles were separated and weighed in addition to weighing the dried unfoliated branch.

For bole sections, the diameters at each end were calculated and dry weight determined from the disk weights. Bole section volume and total bole volume were calculated as truncated cones for each meter. Bole volume was calculated to a 5-cm top. Branch basal area and volume were calculated as a cone; biomass of unfoliated branch, foliated branch, and foliage were calculated from the ratio of the branch collected on that tree and that meter. This proved to be unnecessary since ratios were very similar in the upper crowns of all trees.

All new growth above the last meter was called top and treated as a single branch. This will be evident in the variation in the following tables. On some, such as cumulative foliar mass or stem basal areas, the entire tree was included, and there was a meter 9 on maximum treatment and 7 on minimum. On data such as number or length of branches, the top was excluded, and the upper meter was 6 or 8.

RESULTS

There has been a highly significant response to intensity of culture with the maximum treatment trees having nearly doubled the minimum treatment trees in bole volume and biomass (table 1). The maximum trees are both larger in diameter and height, resulting in highly significant increases in bole size. There were no significant differences in crown biomass with the exception of dead branches, which were highly significantly different. Dead branches accounted for 28 percent of the crown biomass on the maximum treatment but only 6.6 percent on the minimum. Height of live crown explained the big difference in dead branches. The height of live crown was 2.5 m on the maximum treatment but only 0.5 m on the minimum.

Most branches were in the upper crown, and there was a definite die off of branches in lowest m of each crown (table 2). Branch length showed a strong conical form on

Table 1—Comparison of average tree sizes on 10 trees sampled from maximum and minimum treatments

	Maximum	Minimum	Significance
Bole volume (m^3)	0.121	0.056	0.001
Height (*m*)	9.67	7.82	0.001
D.b.h. (*cm*)	17.16	13.62	0.01
Bole biomass (*kg*)	39.81	22.08	0.001
Dead branch biomass (*kg*)	9.36	1.51	0.001
Unfoliated branch biomass(*kg*)	12.79	9.62	NS
Foliated branch biomass (*kg*)	3.41	2.90	NS
Foliage biomass (*kg*)	8.01	8.26	NS

NS = no significance.
Bole volume is to a 5-cm top.

Table 2—Comparisons of tree morphology of maximum and minimum treatments

	Ave. bole diameter		Ave. number of branches		Ave. length of branches		Sum of branch basal area		Foliage biomass	
Meter	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
	- - - *cm* - - -				- - - *cm* - - -		- - - cm^2 - - -		- - - - *gm* - - - -	
1	23.5	18.9	0	1.5	—	149	—	8.1	—	127
2	18.9	14.1	0	5.4	—	220	—	28.9	—	806
3	16.4	13.4	1.1	6.2	354	211	27.5	32.5	201	1,476
4	15.2	10.0	3.4	8.6	287	194	31.1	43.8	611	2,412
5	12.8	8.8	4.3	7.6	276	172	30.7	33.8	905	1,909
6	11.0	8.4	8.7	7.8	226	131	63.4	33.0	2,995	1,121
7	8.4	3.9	5.4	—	181	—	32.1	11.5	1,038	478
8	6.7		7.7	—	148	—	34.4	—	1,795	
9	4.5						16.0	—	782	

Bole diameter is at base of meter, other measures are along the indicated meter. The upper meter of bole diameter, branch basal area, and foliage biomass represents the top.

the maximum treatment with a more oval form for the minimum treatment. The diagonal spacing of a 10- by 12-foot planting is 238 cm, indicating that the lower branches of the maximum treatment had considerable vertical growth. There was strong light competition in the lower 3 m of the maximum treatment. The minimum crowns had just closed during the sixth season, with longest branches at the diagonal spacing.

Foliar biomass was large in both treatments. It was distributed very symmetrically in the minimum treatment but with less regularity and a slight upward skew in the maximum treatment. Branch basal area was distributed similarly to foliar biomass in the upper crown but not in the lower crown of the maximum treatment.

In the upper 4 m, there was a high correlation of branch basal area to foliar biomass on an individual branch basis (r^2 = 0.7-0.9). Accumulating from the top downward, branch basal area explained 97 percent of the change in foliar biomass (fig. 1). At the bottom of the crown the relation became curvilinear. In the upper crown, each cm^2 of branch basal area supported roughly 50 g of foliage. At the bottom of the crown, the value fell to about 20 g per cm^2.

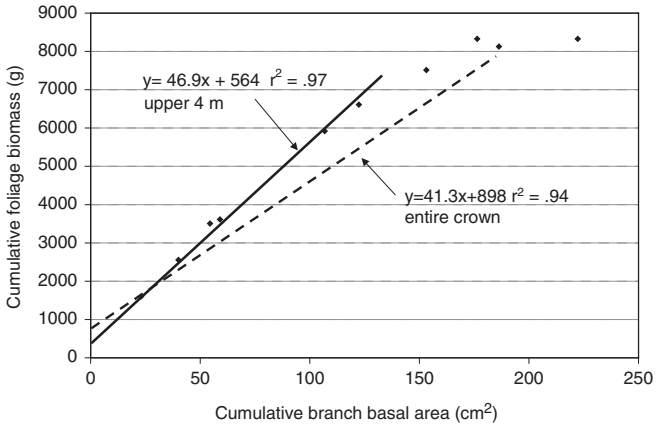

Figure 1—Comparison of branch basal area and foliar biomass. Data are average values for each meter for both maximum and minimum treatments.

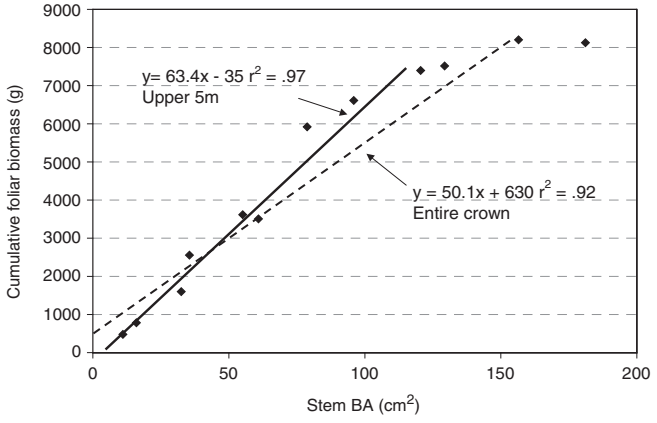

Figure 2—Increase of stem basal area with cumulative biomass from the top of the tree. Data are a composite of both maximum and minimum averages.

The relationship of stem basal area to foliar biomass was very similar to that of branch basal area (fig. 2). This was because stem basal area was nearly equal to cumulative branch basal area, also with an r^2 of 0.96. The relation of stem basal area to foliar biomass had a flat area near the bottom of the tree. Meztger (1893) suggested a relation of stem diameter of the form: Height = a- b (diameter^3), where b is a slope dependent on wood strength and a is the center of the crown mass. The data for both treatment trees fit this relation very well (fig. 3). The intercept of the equation of the maximum treatment was very near the center of the crown as predicted. The minimum treatment equation indicated slightly stronger wood but also estimated the center of the crown above where it actually occurred.

CONCLUSIONS

These data tend to support many of the principles that were outlined in the introduction. Evidence was most convincing that these loblolly pine were growing in accordance with the pipe model of Shinozaki and others (1964). Throughout the upper crown there was a constant ratio of foliar biomass to cumulative branch basal area and stem basal area. Only in the lower crown did this relation break down. The data suggested that each g of needle required 0.02 cm^2 of vascular system to support evapotranspiration.

The data also supported the branch autonomy of Spurgel and others (1991). Below the layer where branches were longer than the diagonal spacing the ratio of foliar biomass to basal area declined. In this zone it was probable that light limits the ability of the branch to maintain leaf replacement. The ratio of foliar biomass to branch basal area dropped to about 20g per cm^2 in the lowest living branches.

Finally there was a very good agreement with Metzger's (1893) relation. He developed the relation assuming that the tree bole should be uniformly resistant to wind on the crown. The relation fits the stem shape of both treatments well and also predicts perfectly the center of the maximum treatment crowns.

It has been difficult to identify any nitrogen relations in this experiment. However, data on leaching of nitrate to the

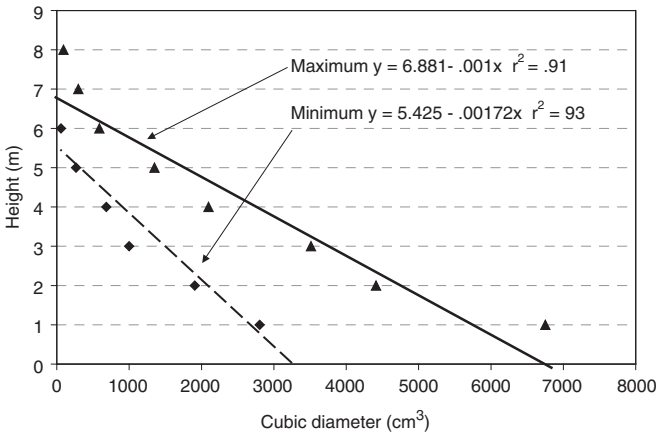

Figure 3—Comparison of stem diameter distribution to cubic distribution described by Metzger (1893).

groundwater suggest that the field had an abundant supply of nitrogen (Williams 1999).

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A BID PRICE EQUATION FOR TIMBER SALES ON THE OUACHITA AND OZARK NATIONAL FORESTS

Michael M. Huebschmann, Thomas B. Lynch, David K. Lewis, Daniel S. Tilley, and James M. Guldin[1]

POSTER SUMMARY

Data from 150 timber sales on the Ouachita and Ozark National Forests in Arkansas and southeastern Oklahoma were used to develop an equation that relates bid prices to timber sale variables. Variables used to predict the natural logarithm of the real, winning total bid price are the natural logarithms of total sawtimber volume per sale, total pulpwood volume per sale, average sawtimber volume per acre, average sawtimber volume per tree, and the ratio of southern yellow pine #2 dimension lumber producer price index (PPI) to pine sawlog PPI. The sawtimber and pulpwood components of these sales were primarily shortleaf (*Pinus echinata* Mill.) pine with some loblolly pine (*P. taeda* L.) for sales occurring in the extreme southeastern portions of the Ouachita National Forest.

A timber cruise is typically conducted to determine sale volume on these sites. The intensity of the cruise is related to sale value, but typical large sales must have a sampling error of ± 10 percent. Sales are then advertised and awarded to the highest bidder. Records for 150 timber sales on the Ouachita National Forest from June 1992 to December 1998 were available for this study. Revenue for each timber sale was obtained by:

Revenue = ($CCFS/PPIS)CCFS + ($CCFR/PPIP)CCFR&T.

The PPI for pine sawlogs (PPIS) was used to deflate the nominal bid price for sawlogs ($CCFS). The roundwood bid price ($CCFR) was deflated by the PPI for pine pulpwood (PPIP). These quantities were multiplied by the hundred-cubic-foot amounts of sawlog (CCFS) and roundwood (including topwood, CCFR&T) to obtain sale revenue.

A number of researchers have used regression analysis to model timber sales in the South, beginning with Guttenburg (1956). Regression analysis yielded the following relationship between real total bid price and the independent variables:

$$\ln(Bid) = b0 + b1 \ln(TSV) + b2 \ln(TPV) + b3 \ln(SVPA) + b4 \ln(SVPT) + b5 \ln(PPIR)$$

where Bid is real winning bid price (thousands of 1996 dollars), TSV is total pine sawtimber volume (thousands of CCF's), TPV is total pine pulpwood volume (roundwood and topwood, CCF's), SVPA is average sawtimber volume (CCF) per acre, SVPT is average sawtimber volume (CCF) per tree, PPIR is producer price index for southern yellow pine #2 dimension lumber divided by sawlog PPI when sale occurred, ln x is the natural logarithm of x, and b0, b1, b2, b3, b4, b5 are estimated coefficients. The fit index for predicting Bid was 0.94 (proportion of total variation in Bid explained by the model). All parameter estimates were significant at the 0.05 level except that corresponding with TVP. However, it was retained because it has been found significant in other studies (Anderson 1976, Buongiorno and Young 1984, Carter and Newman 1998), and its importance was indicated by procurement foresters interviewed as part of the study.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

DEVELOPMENT OF MATURE NATURAL EVEN-AGED STANDS OF LOBLOLLY PINE IN THE PIEDMONT

D.J. Leduc and J.C.G. Goelz[1]

Abstract—In 1949 a loblolly pine growing-space study was established on the Hitchiti Experimental Forest outside Macon, GA. It consisted of 72 plots varying in age from 18 to 88 years old. Of these plots, 20 were part of an embedded thinning study with 2 replications on each of 2 sites and 4 treatments plus a control. Multiple thinnings were conducted, though none in the last 39 years. Diameter, height, and volume increased while the number of trees per acre decreased and stand density index regressed toward a mean value. Generally, these trends are accelerated on plots with higher site indices. Although a density-limiting relationship is suggested by our data, we found that the slope parameter should be -2 rather than -1.605 as suggested by Reineke. This result suggests that basal area alone is a sufficient estimator of stand density.

INTRODUCTION

Loblolly pine (*Pinus taeda* L.) is the most important softwood species in the southern pine region, and 59 percent of this growing stock was in natural stands in 1989 (Schultz 1997). In the future, rotation length is anticipated to increase on public and some nonindustrial private lands.

When Robert Cooper established the Hitchiti growing-space study in 1949, foresters recognized the need to study the relationship between growing space and yield of a stand. Thinning studies reduce the density of a stand, and spacing studies establish a set number of trees per unit area. However, a growing-space study uses both thinning and natural establishment to evaluate the effects of the density of stands on their continued growth.

A growing-space study like this one provides information on growth rates at various densities and also helps to establish the limits of maximum density. This information can be used to construct the stand density management diagrams (Dean and Baldwin 1993, Drew and Flewelling 1979, Gingrich 1967) used for management of loblolly pine stands. The original researchers may not have expected this study to continue into the 21st century, but the longevity of the data collected has added greatly to its value. Most natural resource research organizations and scientists agree that long-term research is essential, yet few carry out studies for more than a few years because of the special problems involved (Devall and Baldwin 1998).

METHODS

Study Site

The growing-space study is located on the Hitchiti Experimental Forest, 20 miles west of Macon, GA, in the lower Piedmont region. The forest has rolling topography with elevations between 328 and 532 feet above sea level. Its soils range from shallow, poorly developed profiles of the Wilkes and Helena series to deep, well-developed soils of the Lloyd and Davidson series. The climate is temperate with a mean annual rainfall of 48 inches and spring droughts expected 1 year out of 5. Almost all of the Hitchiti Forest was previously farmed; continual row cropping caused serious erosion on all of the uplands so that today little topsoil remains. Following agricultural abandonment in the 1860s, 1880s, and 1920s, the stands in this study naturally seeded into almost pure loblolly pine with occasional shortleaf pine (*P. echinata* Mill.) (Brender 1960).

This study was an installation of a broader regional study to determine the relationship between growing space and yield in a stand of natural loblolly pine. At Hitchiti there are seventy-one ¼-acre plots and one 1/10-acre plot with ½-chain-wide isolation strips surrounding each. On 20 plots with a stand density index (SDI) > 293, a thinning study reduced SDI to 275, 225, 175, 125, or left it unaltered as a control. There were four replicates of each treatment. Our description of results concentrates on the thinning-study plots within the larger growing-space study.

At establishment, the plots in this study had ages ranging from 18 to 88 years and site indices (base age 50) ranging from 57 to 105. The plots also had a range of SDI values from 154 to 431. The subset of plots used in the thinning study ranged from age 21 to 30, site index from 65 to 85, and SDI from 293 to 464. By our latest measurement, in winter 2002, 53 years had passed since study establishment. Of the 72 original plots, 24 have been lost to harvest or damage, and the stand ages now ranged between 71 and 142. Hardwood trees were poisoned on all plots in 1956 and again partially cut in 1993.

Analysis

We chose to describe stand dynamics over the 27-year period following the last thinning. Rather than testing whether the treatments were significant, we describe the subsequent development of plots that initially differed due to site and previous management. We calculated site index based on a sample of tree heights and ages taken in 1949 using the equation for loblolly pine in the South (U.S. Department of Agriculture 1929), as formulated by

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Carmean and others (1989). When we explored the limiting relationship between trees per acre and quadratic mean diameter, we supplemented the thinning study data with the data from the other plots of the growing-space study. We wanted sufficient numbers of observations near the limiting density. Our analysis examines patterns of stand development by graphing stand-level variables (including only pine trees). The variables are (1) number of trees per acre, (2) average height, (3) quadratic mean diameter, (4) SDI (Reineke 1933), (5) cumulative yield (including thinnings) in cubic-foot volume, (6) cumulative yield in board-foot volume, (7) mean annual increment in cubic-foot volume, (8) mean annual increment in board-foot volume, and (9) percent of pine (by basal area). We calculated tree volumes in cubic feet and in board-foot volume by the International ¼-inch log rule. These calculations used the taper functions of Farrar and Murphy (1987, 1988) as incorporated in an unpublished FORTRAN program by Murphy and Leduc. The cumulative yields include only volumes removed during the 53 years of the study; if previous harvests were made, that volume is missing. Each plot is connected by lines to show its individual trajectory and is identified symbolically by the level of thinning and site quality of the stand. In addition, we plotted percent of pine vs. total basal area. Plot 43 is excluded because its extreme age (144) and low percentage of pine (74) compress the remaining plot data and thus hide other potential trends. As well, hardwoods were not controlled on plot 43 in 1993. To explore a limiting density relationship, we plotted the logarithm of trees per acre vs. the logarithm of quadratic mean diameter and estimated a limiting density line for that data.

We modeled the limiting density relationship as trees per acre vs. quadratic mean diameter, which is the standard Reineke (1933) relationship.

$$N = aD_q^{\,b}, \qquad (1)$$

where

N = number of trees per acre

Dq = quadratic mean diameter

a and b = parameters to be estimated.

Reineke set b to be -1.605. Equation 1 is often represented by the log-log transformation:

$$\log(N) = \log(a) + b * \log(D_q), \qquad (2)$$

We estimated equation 2 using a weighted regression to provide a line near the limits of the data. Specifically the weighting function was

$$wt = \left(\frac{ba - ba_{\min}}{ba_{\max} - ba_{\min}} \right)^{1000}, \qquad (3)$$

where

wt = the weight

ba = basal area

ba_{min} = the minimum basal area among the data

ba_{max} = the maximum basal area among the data.

The exponent of 1000 was chosen as the largest power of 10 that could be used without causing overflows on the computer. The idea was to give large weight to observations near the boundary line.

RESULTS AND DISCUSSION

We present the relationship of higher hardwood basal area with increasing age and decreasing basal area in figure 1. There is a slight tendency for percent of pine to decrease

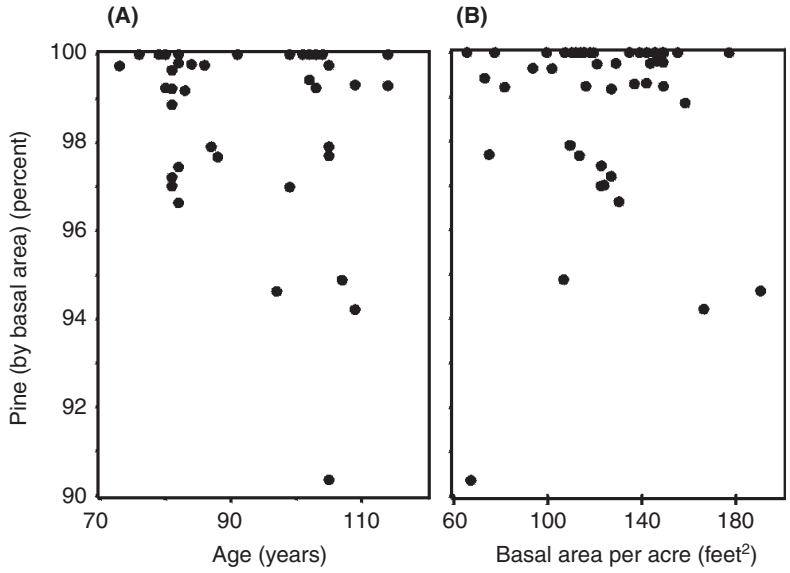

Figure 1—Hardwood encroachment on all study plots as illustrated by (A) percent of pine basal area vs. age and (B) percent of pine basal area vs. total basal area.

with increasing age. Either relationship could exist, but prior removals, the relatively poor sites, or other factors may have eliminated any meaningful age–basal area relationships.

We present basic stand growth relationships in figure 2. Over time the number of trees per unit area decreases (fig. 2A). The plots with higher site index have already completed much of their thinning. The Sukatschew effect suggests stand development progresses faster on better sites (Harper 1977). Average stand height increases as stands get older (fig. 2B). As expected, the plots with higher site index are generally taller than those with lower site index.

Diameter increases as trees get older. On better sites and with lower densities, the absolute diameter is greater. However, the rate of increase is about the same for all sites and densities (fig. 2C). This result suggests that the plots are currently within a relatively narrow band of stand density. Trends in SDI are somewhat masked by a general regression toward the mean (fig. 2D). The plots with higher SDI (> 250) at age 50 to 60 tend to decrease in density, while the plots that have lower SDI (< 200) tend to increase over time.

In figure 3 we present trends in volume growth as total yields and increments. As expected, total yield (board foot and cubic foot) increases with age. The plots thinned to 175 SDI have the greatest volume yield. Volume mean annual increment trends suggest that a rotation of around 70 years would maximize production. Plots thinned lightly on poor sites have (MAI) trends in board-foot volume that are still increasing at age 85.

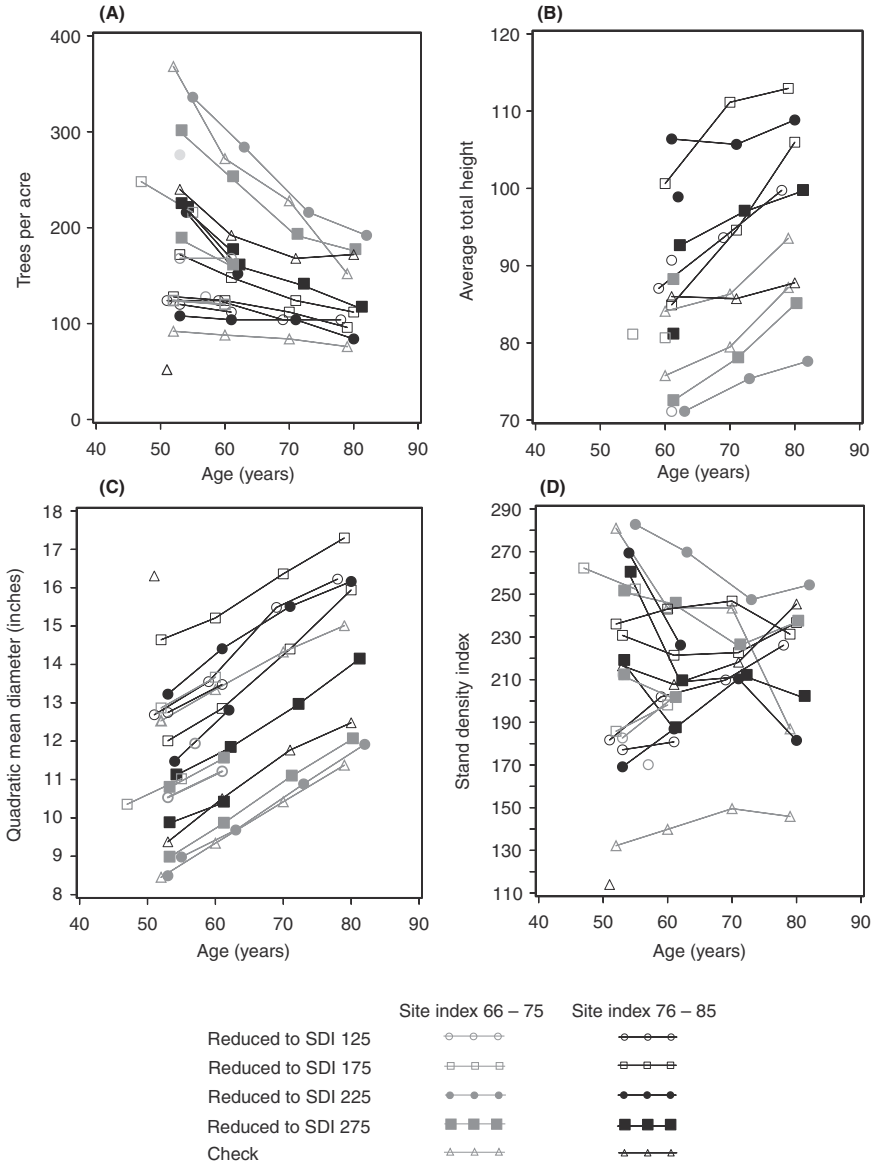

Figure 2—Basic stand growth relationships in the thinning study as related to age including (A) trees per acre, (B) average total height, (C) quadratic mean diameter, and (D) stand-density index (SDI).

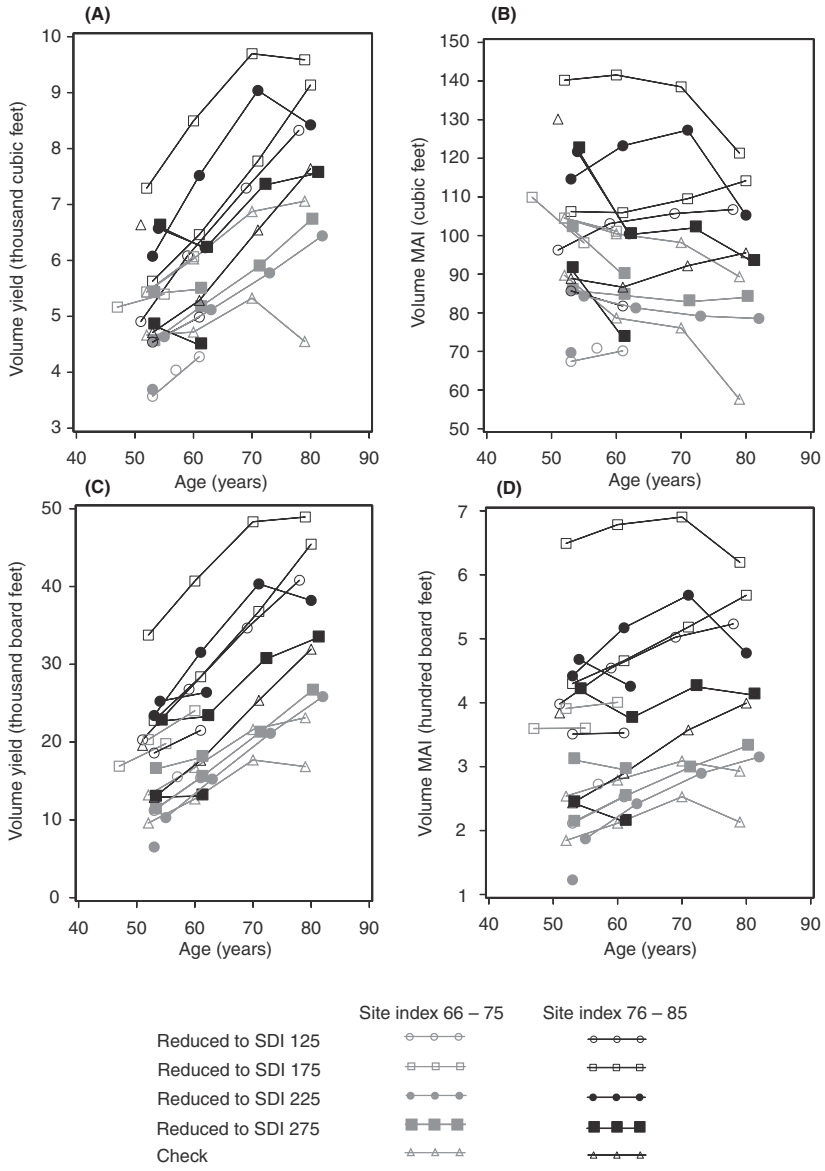

Figure 3—Volume-growth relationships in the thinning study as related to stand age including (A) cubic-foot volume yield, (B) mean annual increment of cubic-foot volume, (C) board-foot volume yield in International ¼-inch scale, and (D) mean annual increment of board-foot volume in International ¼-inch scale (stand-density index = SDI, MAI = mean annual increment).

In figure 4 we show the relationship between trees per acre and quadratic mean diameter on a log-log scale. The limiting density relationship has a slope of -2.005 rather than the -1.605 assumed in the Reineke relationship. Statistically, this slope of -2.005 is not significantly different (α = 0.05) from -2, indicating that these stands are limited by basal area since basal area is proportional to the square of diameter. Contrary to most density management tools (Dean and Baldwin 1993, Gingrich 1967, Reineke 1933), this result suggests that, for natural stands of loblolly pine, the same maximum basal area applies regardless of age or average tree size. Thus basal area alone is an adequate measure of stand density.

We fit equation 2 while fixing *b* to be 2.0, using the same weighting function. Thereby we hope to determine the value of the limiting basal area (with *b* as -2.005, the limiting basal area varies very slightly with increasing quadratic mean diameter). There is once again a clear boundary, as shown in figure 5, which we have calculated as 183.2 square feet (1/183.2 = 0.005458).

Nelson and Brender (1963) indicated that basal area was a better predictor variable for estimating future volume growth than was SDI and the Hitchiti plots were a subset of their data. However, Nelson and Brender's (1963) results prove little; standing volume was greatly superior to basal area as a predictor variable. SDI is intended as an estimate of density, not as an estimate of future volume growth. SDI will not be an effective predictor variable unless other predictor variables contribute information regarding age and average tree size. A more appropriate statistical test would be

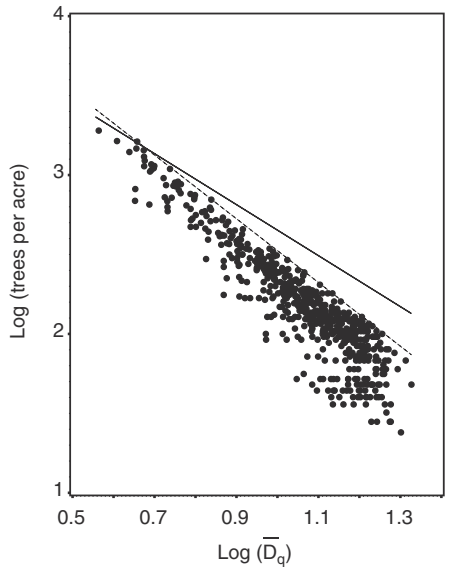

Figure 4—The relationship between the number of trees per acre and the quadratic mean diameter on a log-log scale. Superimposed on this graph is the line for the Reineke slope of -1.605 (solid line) and an apparently better-fit line with a slope of -2.005 (dashed line).

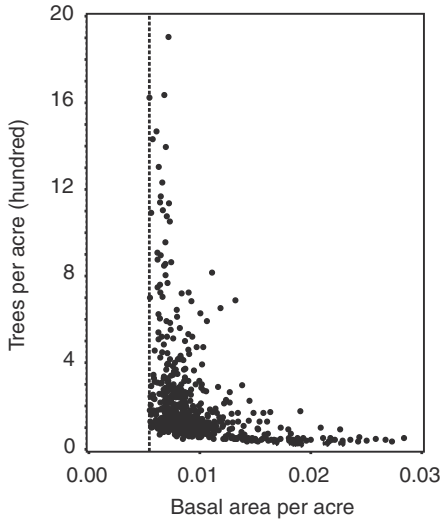

Figure 5—The relationship between trees per acre and the inverse of basal area per acre. Superimposed on this graph is a dotted line showing the hypothesized basal area limit of 183.2 square feet per acre.

whether SDI was a significant predictor variable in an equation that already had basal area as a predictor.

The idea of a limiting basal area also suggests other processes in stand dynamics. As the proportion of sapwood basal area to total basal area declines with age, and as sapwood basal area is related to foliage mass, foliage mass would be lower in an older stand than a younger stand, even though both were at the boundary of maximum density.

CONCLUSIONS

The Hitchiti plots in our report are rare in their age range and the length of recorded data, but they appear to behave mostly as one would expect a natural stand of loblolly pine to behave. The small percentage of hardwood encroachment and the relatively late culmination of MAI are probably related to the relatively poor sites. The indication that basal area defines the limiting density of these stands could be related to the site quality, or it could be more significant. We intend to follow up on basal-area limitation with other research data in the near future. Finally, we will continue to collect data from these stands for as long as the plots avoid catastrophic mortality. The trends may not be surprising, but do provide hard numbers for use in judging the results of the increasingly long rotations in public forests.

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ESTIMATION OF REINEKE AND VOLUME-BASED MAXIMUM SIZE-DENSITY LINES FOR SHORTLEAF PINE

Thomas B. Lynch, Robert F. Wittwer, and Douglas J. Stevenson[1]

POSTER SUMMARY

Maximum size-density relationships for Reineke's stand density index as well as for a relationship based on average tree volume were fitted to data from more than a decade of annual remeasurements of plots in unthinned naturally occurring shortleaf pine in southeastern Oklahoma. Reineke's stand density index is based on a maximum line of the form log(N) = a + b(log(D)) where N is trees per acre, D is quadratic mean diameter, and a and b are constants. Reineke (1933) proposed a value of b = -1.6 for many tree species. However, he obtained a steeper slope for shortleaf pine (b = -1.8). The -3/2 power law is based on a maximum line in the form log(V) = a' + b'log(N), where V is mean tree volume and a' and b' are constants. A value of -3/2 has been postulated for the slope parameter b' for many plant species (Yoda and others 1963). Drew and Flewelling (1977) applied this equation to forest populations and noted the relationship to Reineke's maximum size-density equation. Intercept values a and a' for each of the approaches are species dependent. The two maximum size-density lines were fitted to the shortleaf pine plot data from unthinned plots in shortleaf pine natural stands. These lines can be used to calculate Reineke's stand density index and to evaluate the likelihood of competition-induced mortality for shortleaf pine forests.

Unthinned plot data are from two study sites located in naturally occurring shortleaf pine forests in the Ouachita Mountains of Pushmataha County, OK. Site One is about 25 miles east of the western limit of the natural range of shortleaf pine, whereas Site Two is located an additional 35 miles to the southeast. A thinning study that included the unthinned control plots used here was installed on Site One during the winter of 1989 in stands aged 25 to 30 years and on Site Two during the winter of 1990 in stands aged 30 to 37 years. Fourteen annual measurements have been made at Site One and 13 at Site Two. Annual measurements from three unthinned control plots located at each site provided data for examination of maximum size-density relationships. Thinned plots were not used in the current analysis. Measurement plots from Site One were 0.1 acre in size whereas plots on Site Two were 0.2 acre.

The Durban-Watson test indicated autocorrelation in these data, which was not unexpected because plots were measured annually. Therefore, a first difference model was used to estimate the slope parameter for a Reineke-type maximum size-density relationship. The intercept was obtained by constraining the relationship to pass between the means of the dependent and independent variables. Then the standard error of the residuals was calculated. The following maximum line was obtained by adding two standard errors (standard error of the residuals) to the intercept

$$\log(N) = 4.3275 - 1.7197[\log(D)]$$

where log(N) is the common (base 10) logarithm of number of trees per acre and log(D) is the common logarithm of quadratic mean d.b.h. This yields a maximum Stand Density Index (SDI) of 405 trees per acre where SDI is the expected maximum density for a stand having a quadratic mean d.b.h. of 10 inches. Preliminary analysis of the relationship between mean volume and maximum density indicated that the slope was not substantially different than the theoretical value of –3/2 for these data. An intercept was obtained for this line using methods similar to those described for the Reineke-type line.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

LONG-TERM RECORDS OF SOUTHERN PINE DYNAMICS IN EVEN-AGED STANDS

J.C.G. Goelz, J.H. Scarborough, Jr., J.A. Floyd, and D.J. Leduc[1]

The timber management research work unit of the U.S. Department of Agriculture Forest Service in Pineville, LA (SRS-4111) oversees many long-term studies in stand dynamics; we summarize current studies in table 1. We remeasure > 700 plots established in even-aged stands of southern pines at approximately 5-year intervals; some plots have measurements spanning > 50 years (table 1). These plots largely came from silvicultural studies investigating the effects of establishment methods, initial spacing, and subsequent thinning. There are studies in loblolly (*Pinus taeda* L.), longleaf (*P. palustris* Mill.), slash (*P. elliottii* Engelm.), and shortleaf (*P. echinata* Mill.) pine. The majority of the studies are in artificially regenerated stands; however, one study examines thinning in naturally regenerated loblolly pine. Fertilization, prescribed burning, pruning, and other silvicultural practices were tested in some of the studies; in other cases, the specific silvicultural practices varied across studies, reflecting local practices. While some studies reflect practices that are rarely applied now, such as direct seeding of southern pines, they provide a rare and valuable historic database. Data from these studies provide a point of comparison for current practices from a wide range of conditions that is biologically interesting, such as natural thinning in very dense stands. Long-term records available for plantations > 60 years old are particularly noteworthy. While most of our data reflect artificial regeneration practices of 20 to 70 years ago, we are revitalizing our long-term database with the addition of new plots in young, operationally established plantations with the cooperation of public and private forest land managers. Our data continue to be available to interested cooperators.

Table 1—Studies in growth and yield of even-aged pine stands that are maintained by SRS-4111

Emphasis of study	Species (pine)	Regeneration technique	Year of stand origin	Current plots[a]	Study number
Fire, spacing, pruning, thinning	Longleaf	Planted	1935	32	2.03
Fire, spacing, pruning, thinning	Longleaf	Planted	1935	64	3.02
Thinning, fertilization, clover, forage production	Longleaf	Planted	1952	24	2.29
Thinning	Longleaf	Planted	1945	18	3.12
Thinning	Longleaf	Planted	1940 – 1941	42	3.13
Effect of site on growth of unthinned plantations	Longleaf	Planted	1940 – 1958	47	3.29
Thinning, initially site preparation	Loblolly	Planted	1970 – 1973	17	2.21
Thinning, pruning, (sudden sawlog)	Loblolly	Planted	1944	12	4.1
Spacing and thinning	Loblolly	Planted	1952	88	3.22
Spacing and site effects on growth of unthinned plantations	Loblolly	Planted	1928 – 1968	16	3.30
Thinning, site preparation	Loblolly, slash	Planted	1964	24	5.12
Compare row and selective thinning	Slash, loblolly	Planted	1953 – 1960	7	3.33
Thinning	Slash	Planted	1941	36	3.05
Thinning	Slash	Planted	1948	38	3.06
Thinning	Slash	Planted	1948 – 1950	40	3.14

(continued on next page)

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Table 1—Studies in growth and yield of even-aged pine stands that are maintained by SRS-4111 (cont.)

Emphasis of study	Species (pine)	Regeneration technique	Year of stand origin	Current plots[a]	Study number
Spacing, thinning	Slash	Planted	1977	31	3.34
Spacing	Loblolly	Seeded	1971	28	3.23
Spacing	Loblolly	Seeded	1971	28	3.25
Spacing	Slash, loblolly, longleaf	Seeded	1965	54	3.15
Spacing	Slash	Seeded	1968	18	3.19
Spacing	Slash	Seeded	1962	7	3.10
Precommercial thinning	Longleaf	Seeded	1961 – 1962	24	3.20
Precommercial thinning	Longleaf	Seeded	1965	15	3.31
Precommercial thinning	Slash loblolly, longleaf	Seeded	1987	24	2.37
Precommercial thinning	Loblolly	Seeded	1964	18	3.18
Precommercial thinning	Loblolly	Seeded	1966	15	3.21
Precommercial thinning	Loblolly	Seeded	1958	26	3.07
Precommercial thinning	Slash	Seeded	1964	18	3.17
Precommercial thinning	Slash	Seeded	1968	18	3.24
Current management practices of broad range of owners	Longleaf loblolly, slash	Planted	1990+	Plots being added	OPS
Thinning, growing space study	Loblolly	Natural	1861 – 1949	59	NEAL
Choice of species, soil-site evaluation	Loblolly, longleaf, slash, shortleaf	Planted	Mid 1950s	< 135	1.1

[a] Current number of plots may be much fewer than initial numbers due to attrition.

Upland Hardwoods — Natural Regeneration

Moderator:

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Southern Research Station

FIRST-YEAR EFFECTS OF SHELTERWOOD CUTTING, WILDLIFE THINNING, AND PRESCRIBED BURNING ON OAK REGENERATION AND COMPETITORS IN TENNESSEE OAK-HICKORY FORESTS

Samuel W. Jackson and David S. Buckley[1]

Abstract—Oak regeneration has declined significantly over the past century in many regions of the United States. Prescribed burning, herbicides, and cutting are all potentially viable methods of favoring oak regeneration by removing competitors, but evaluation of these methods in all regions of the Eastern United States is incomplete. We compared effects of four treatments on oak regeneration and competitors: Shelterwood cutting, wildlife thinning using herbicide, wildlife thinning using herbicide combined with prescribed burning, and prescribed burning with no overstory treatment. Light, soil moisture, herbs, shrubs, woody reproduction, and overstory structure were measured to quantify treatment effects. Shelterwood harvests and wildlife thinnings significantly increased light availability and reduced overstory and midstory cover. Prescribed fire significantly increased the density of oak seedlings and sprouts < 10 cm tall. Prescribed fire also reduced the density of red maple regeneration, but significantly increased the density of sassafras and yellow-poplar regeneration.

INTRODUCTION

Eighty-nine percent of Tennessee's 14.1 million acres of forestland is classified as hardwood forest with 45 percent of the hardwood timber volume comprised of oak (*Quercus* spp.) (Schweitzer 2000). Nationally, oak ecosystems occupy 114 million acres and provide habitat for more than 75 associated tree species and 230 species of wildlife (Rogers and others 1993). Certain oak species form a cornerstone of the forest products industry in Tennessee and the remainder of the United States. In addition to oak timber, oak ecosystems provide a number of recreation opportunities, including bird watching, hunting, hiking, and camping. The net economic impact of oak ecosystems is difficult to estimate but exceeds that of oak timber alone.

Due to the high ecological and economic importance of oak, the current failure of oak species to regenerate across the Eastern United States has attracted considerable attention. It is widely held that oak regeneration failures represent a prominent silvicultural problem (Van Lear 1990). Upland oak species are generally favored by disturbance such as periodic fire (Abrams 1992), and much of the oak-dominated forest we have today developed following disturbances such as clearing land for agriculture, burning, and logging in the late 19th and early 20th centuries (Clark 1993, Crow 1988). As oak stands originating after these disturbances have matured and developed dense canopies, species such as maple (*Acer* spp.) and beech (*Fagus* spp.) that are more shade tolerant and fire intolerant than oak have begun to dominate the understory and middlestory (Abrams 1992). Complete canopy removal tends to release these tolerant species and hasten the replacement of oak. Yellow-poplar (*Liriodendron tulipifera*) is also less tolerant of fire than oak and can be a significant competitor in large openings created by harvests (Loftis 1990). Past research suggests that oak regeneration failures are more common on high-quality sites where competitors such as yellow-poplar and red maple (*A. rubrum*) have a competitive advantage over oaks (Oak 1993). Oak regeneration is often more successful on poor-quality sites, where large root systems and other adaptations to drought give oak the advantage over these competitors (Abrams 1990).

The effects of most disturbances in the forest, including fire, are to increase light availability, reduce competition, and increase the growing space for oaks. Although oaks are intermediate in tolerance of shade, prolonged shading can lead to seedling mortality (Crow 1988). Carvell and Tryon (1961) indicated that of all the environmental factors at a particular site, light intensity was most strongly correlated with the density of oak seedlings, and that oak regeneration was more abundant on disturbed sites than undisturbed sites. Other factors, such as soil moisture and nutrient levels, can also significantly impact seedling establishment (Crow 1988).

A wide range of mechanical, chemical, and prescribed burning methods are available for removing overstory and middlestory stems to reduce competition and increase the survival and growth of oak in the understory. Shelterwood and shelterwood-burn techniques for facilitating the regeneration of oak species have been investigated and show promise (Brose and others 1999, Keyser and others 1996, Loftis 1990). Several studies have indicated that prescribed fire is a valuable tool for controlling less fire-tolerant competitors (Barnes and Van Lear 1998, Huddle and Pallardy 1999). An alternative method to overstory removal via harvesting is the use of herbicides. The girdling and treating of individual trees with herbicides reduces competitive effects of the overstory and midstory vegetation layers, without the level of soil disturbance associated with logging. Herbicides, when applied as recommended by the manufacturer, generally do not have significant effects on the environment and efficiently increase light and growing space for vegetation (Morrison and Meslow 1983).

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In 2001, we examined the initial, first-year effects of several potentially interacting factors on oak regeneration in a study designed to compare the effectiveness of shelterwood cutting, wildlife thinning using herbicide, wildlife thinning using herbicide combined with prescribed burning, and prescribed burning alone for improving oak regeneration and wildlife habitat.

Specific objectives of this research were to (1) evaluate the effectiveness of shelterwood cutting and wildlife thinning with herbicide for increasing oak regeneration success; (2) test the hypothesis that prescribed fire enhances the positive effects of these treatments on oak regeneration; and (3) establish the impact of all treatment combinations on potential competitors of regenerating oaks.

METHODS

Study Area

This study was conducted at Chuck Swan State Forest and Wildlife Management Area in eastern Tennessee, a 9,700-ha peninsula in Norris Lake co-managed by the Tennessee Division of Forestry and the Tennessee Wildlife Resources Agency for timber production and recreation such as hunting, hiking, and wildlife viewing.

The primary cover type of Chuck Swan is mixed hardwoods. Predominant species include white oak (*Q. alba*), chestnut oak (*Q. montana*), black oak (*Q. velutina*), scarlet oak (*Q. coccinea*), blackgum (*Nyssa sylvatica*), red maple, and yellow-poplar. The terrain of Chuck Swan is hilly with elevations ranging from 305 m to over 488 m above sea level. Temperatures on the area range from a yearly average high of 20.4 °C to a yearly average low of 7.9 °C. The area receives approximately 1193.8 mm of rain per year (NCDC 2001). Soils were Ultisols of three series: Fullerton, Bodine, and Clarksville (Soil Survey Division 2002).

Four 9.7-ha stands on moderately productive sites were delineated for study. Site index was approximately 20 m for oak at base age 50 (Personal communication. Darren Bailey. 2002. Forester, Chuck Swan State Forest, 3476 Sharps Chapel Road, Sharps Chapel, TN 37866). All study sites were located on northwest aspects, with slopes averaging 24 to 30 percent. All stands were comprised of mixed (oak-hickory) hardwoods with a small component of pine.

Treatments

Five different treatments and a control were implemented for this study. The treatments were a prescribed burn alone with no overstory treatment, shelterwood harvest unburned, shelterwood harvest with prescribed burning, wildlife thinning using herbicides, and wildlife thinning using herbicides combined with prescribed burning. The shelterwood-burn treatment (Brose and others 1999) will be burned in 2005 and is currently incomplete. Each treatment was randomly assigned to a 0.81-ha cell. Two cells in each stand received each treatment. The shelterwood-cutting treatment was assigned to four cells in each stand, with two cells scheduled to be burned in 2005 to complete the shelterwood-burn treatment. The data from the two shelterwood treatments were analyzed separately to maintain a balanced design, although no significant differences between these treatments were expected.

The wildlife thinnings were designed to enhance habitat and food production for wildlife with no timber production concerns considered. Trees that were marked to be treated were species of lesser benefit to wildlife, such as red maple and yellow-poplar. A target residual basal area of 11.5 m^2 per ha was established. In cases where overstory oaks occurred in high density, some oaks had to be treated to achieve the target basal area. Trees selected for removal were treated with Garlon 3A® after they were either girdled with a chainsaw or hatchet, or felled. As recommended by the manufacturer's representative, Garlon 3A® was applied in a 50/50 mixture with water to treat all cut surfaces on girdled trees and stumps. No trees or debris were removed from the site. All stands were treated in late February to early March 2001.

Prescribed burning was conducted on the uncut-burn and wildlife thinning with prescribed burning treatments in April 2001. No precipitation occurred within 3 days of the burn in any stand. The average high temperature during the burns was 25 °C and the average low was 10 °C. Relative humidity on the burn days averaged 54 to 66 percent. Fire intensity was estimated based on average flame lengths. Flame lengths for most burned areas averaged 1 m.

The shelterwood harvests were completed between June 19 and July 20, 2001. Timber marking was carried out based on timber production and regeneration goals. The goal of the harvest was to have a residual basal area of approximately 11.5 m^2 per ha. Trees that were left were of good quality, as vigorous as possible, and of good form. Whenever possible, oak stems were left as residual stems. Species removed included American beech (*Fagus grandifolia*), red maple, sassafras (*Sassafras albidum*), and hickory (*Carya* spp.). Harvesting was completed by a contract logging crew.

Measurements

Pre- and posttreatment data were collected in August and September 2000 and 2001, respectively. Three permanent sampling plots were established within each 0.81-ha treatment cell. To prevent edge effect and measurement overlap, each plot was at least 30.5m from the cell edge and at least 30.5 m from another plot.

Herb species and cover were recorded in each sampling plot using a line-intercept method. Three transects, each 11.3 m long, were established radially around plot center on bearings of 0, 120, and 240 degrees. A measuring tape was stretched along the length of each transect. Wherever an herbaceous plant intersected the tape, its coverage of the tape was recorded to the nearest centimeter for calculation of percent cover. Woody regeneration was tallied using a 3.6-m radius circular plot. Within this plot, all woody stems 140 cm tall and shorter were counted. The count was organized by species and height class. Two height classes were used: stems less than 10 cm tall, and those 10 cm to 140 cm tall. Woody saplings were tallied within a 5.7-m radius circular plot. All woody stems greater than 140 cm tall and up to 11.4 cm in diameter at breast height (d.b.h.) were tallied. The data were collected by species.

Overstory tree data were obtained within an 11.3-m radius circular plot. Tree diameter and species were recorded for trees larger than 11.4 cm in d.b.h. Overstory basal area was calculated from the diameter measurements of overstory trees.

Canopy cover was estimated with a handheld spherical densiometer (Forest Densiometers Inc., Bartlesville, OK) in 2001. Readings were taken at points 5.6 m from plot center in each of the four cardinal directions. Four measurements were taken at each of these four sampling points, one in each cardinal direction. This method resulted in a total of 16 measurements per plot.

Measurements of photosynthetically active radiation (PAR), the wavelength increment of light that plants use to conduct photosynthesis, were taken with an AccuPAR Ceptometer (Decagon Devices Inc.; Pullman, WA). Measurements were taken in September 2001 along the same three transects used for herbaceous measurements. Measurements were taken at plot center and at the midpoint and endpoint of each transect. Two measurements were taken at each point. One measurement was taken at 32.5 cm above the ground to measure light at the level of small seedlings and herbs. The other measurement was taken at approximately 100 cm above ground to measure light at the sapling and shrub level. Seven measurements were taken at each sampling plot for each height, resulting in a total of 21 samples in each treatment cell. Reference measurements were taken in the open just before and after sampling in the stands to calculate percent full PAR at each measurement point. Light measurements were taken on cloudless days from 10:00 a.m. until 2:00 p.m. to minimize effects of low-sun angles.

Soil-moisture measurements were collected over 2 days in October 2001. No measurable precipitation had occurred within 4 days of the measurements. Percent volumetric soil moisture was measured using a Trase TDR soil-moisture probe (Soil Moisture Equipment Corp; Goleta, CA). One measurement was taken at each plot center, totaling three per treatment cell.

Data Analysis

Means for each plot were calculated and analyzed using Analysis of Variance General Linear Model (GLM) procedure; (SAS Institute 2000). Class variables used were stand and treatment. The GLM procedure tested for differences between stands and treatments using the stand-treatment interaction as an error term to account for variation between stands with $\alpha = 0.05$. Means were separated using Tukey's mean separation technique with $\alpha = 0.05$. Data found to be nonnormal in distribution were transformed by taking natural logarithms. Means presented in the results are calculated from the raw data.

RESULTS

As expected, significant differences in canopy cover were detected among treatments ($P = 0.0001$) (fig. 1). Increased overstory removal decreased canopy cover. Prescribed burning also affected canopy cover, either by further

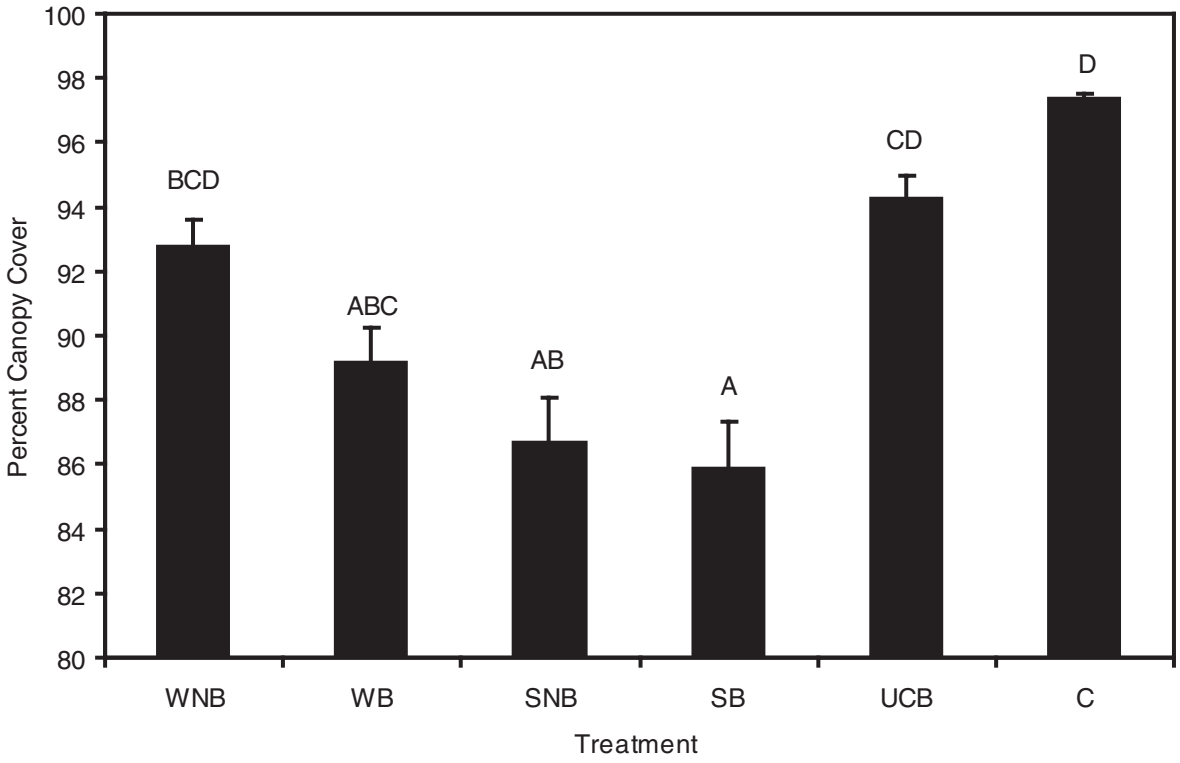

Figure 1—Percent canopy cover by treatment. Error bars represent one standard error beyond the mean. Means with similar letters are not significantly different. If no letters are present for a particular set of means, no statistically significant separation was found. SB = Shelterwood Cut Designated to be Burned; SNB = Shelterwood Cut Designated to Remain Unburned; WB = Wildlife Thinning Prescribed Burned; WNB = Wildlife Thinning Unburned; UCB = Uncut Prescribed Burned; C = Control.

reducing levels of cover when combined with the herbicide treatments or by reducing cover to a lesser degree when used alone.

Significant differences in PAR levels at 100 cm above the ground were detected between treatments (P = 0.0001) (fig. 2). The control had significantly lower PAR availability than all other treatments. Any cell that received a treatment exhibited increased levels of light (PAR) availability over the control. A similar pattern occurred in measurements taken at 30.5 cm above the ground, although these PAR levels were slightly lower than PAR at 100 cm above the ground across all treatments. Differences in PAR availability at 30.5 cm between treatments were very significant (P = 0.0001). The control had significantly lower PAR at this height than any other treatment except the uncut burned treatment. The uncut burned treatment had significantly lower light levels than the shelterwood treatment designated for burning. Any treatment involving overstory removal increased light (PAR) availability.

There were no significant differences in percent soil moisture between treatments (P = 0.2264). Mean percent soil moisture ranged from 12.8 to 16.03 percent.

Density of chestnut oak regeneration under 10 cm tall differed significantly among treatments (P = 0.0334) (table 1). Tukey's mean separation showed that the prescribed burned wildlife thinning had significantly more chestnut oak stems per ha than the shelterwood cut not to be burned. The raw means indicated that the control and the uncut burned areas had more chestnut oak stems than the prescribed burned wildlife thinning. There were no significant differences in the density of chestnut oak regeneration over 10 cm tall between treatments (P = 0.1011).

Red oaks, including northern red (*Q. rubra*), black, and scarlet oaks, were analyzed as a group. The number of red oak stems per ha less than 10 cm tall did not significantly differ between treatments (P = 0.1795) (table 1). The means, though not significantly different, indicate differences between the burned and unburned treatments, with more stems less than 10 cm tall occurring in burned areas. No significant differences between treatments (P = 0.1511) were found in the number of red oak stems per ha over 10 cm tall. However, fewer red oak stems over 10 cm tall were found in treatments involving prescribed burning. The shelterwood treatments also exhibited some loss of red oak stems greater than 10 cm tall.

No significant differences between treatments were found in white oak stems per ha less than 10 cm tall (P = 0.0964) (table 1). However, the means indicate that nearly 9 times more white oak stems under 10 cm tall were present in prescribed burned treatments than in unburned treatment. Between treatment differences in white oak stems per ha over 10 cm tall were marginally significant (P = 0.0529). The unburned wildlife thinning had significantly more white oak stems over 10 cm tall than the prescribed burned wildlife thinning. Burning significantly reduced the density of white oak stems greater than 10 cm tall.

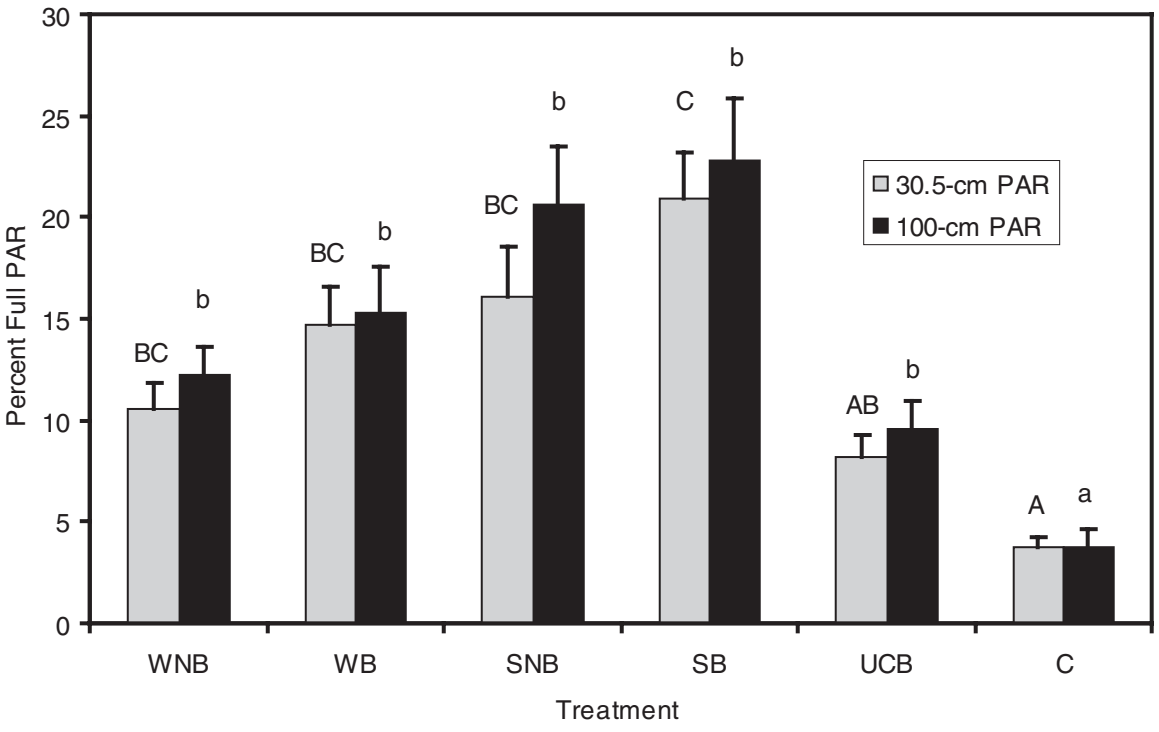

Figure 2—Percent full PAR by treatment. Error bars, significant differences, and treatment codes as in figure 1. Lower case letters were used for 1 m PAR and capital letters were used for 30.5 cm PAR.

Table 1—Mean density of woody regeneration under 1.4 m tall per ha by treatment and species

Species	Height	Treatment					
		C	UCB	WNB	WB	SNB	SB
	cm						
Chestnut Oak	10-140	16 237	3 174	10 913	6 317	4 330	4 586
	< 10	3 286ab	4 484ab	2 395ab	2 600a	921b	1 986ab
Red Oaks	10-140	1 290	2 918	3 686	1 054	983	2 293
	< 10	235	1 065	461	543	123	512
White Oak	10-140	1 003ab	532ab	1 463a	430b	829ab	543ab
	< 10	184	5 242	584	6 849	113	778
Red Maple	10-140	31 583	17 752	29 464	15 428	23 905	20 291
	< 10	21 222	16 155	26 648	11 538	13 657	15 418
Sassafras	10-140	2 027	8 835	4 505	21 386	1 904	2 867
	< 10	717	23 086	829	47 912	737	2 631
Yellow-Poplar	10-140	410	1 884	1 014	3 634	1 044	942
	< 10	184a	31 664a	635ab	25 860a	307b	225ab

C = control; UCB = uncut prescribed burned; WNB = wildlife thinning unburned; WB = wildlife thinning prescribed burned; SNB = shelterwood cut designated to remain unburned; SB = shelterwood cut designated to be burned.
Densities with the same letters are not significantly different between treatments. If no letters are present, no statistically significant differences were found.

Before and after treatments, oak saplings greater than 140 cm tall but less than 11.4 cm in d.b.h. were exceedingly rare and highly variable in distribution across the study area, which precluded statistical analysis of the density of oak in this size class. The virtual absence of large oak saplings highlights the lack of oak regeneration success in the area.

Two of the major competitors of oak regeneration, yellow-poplar and sassafras, showed posttreatment increases in the density of stems under 10 cm tall (table 1). Significant posttreatment differences were detected in the density of yellow-poplar stems per ha under 10 cm tall ($P = 0.0041$). The prescribed burned wildlife thinning and the uncut burned treatment had significantly more yellow-poplar stems under 10 cm tall than the shelterwood cut to remain unburned and the control. This increase far exceeded the number of yellow-poplar stems present before burning that could have produced post burn sprouts. Thus, prescribed burning significantly increased yellow-poplar density. Density of yellow-poplar stems over 10 cm tall differed significantly between treatments ($P = 0.0279$). Tukey's mean separation did not find any differences, however, between treatments. Pre- and posttreatment means indicate prescribed burning increased the density of yellow-poplar in this size class as well. The uncut burned treatment and prescribed burned wildlife thinning had significantly more sassafras stems less than 10 cm tall than in any other treatment. Posttreatment differences in sassafras stems per ha greater than 10 cm tall were marginally significant ($P = 0.0553$). Sassafras over 10 cm tall was most abundant in prescribed burned treatments.

Red maple regeneration under 10 cm tall did not significantly differ between treatments ($P = 0.0879$) (table 1). However, means indicate that any treatment involving site disturbance or prescribed burning reduced red maple density relative to pretreatment densities, whereas red maple density in the control increased. Differences in red maple stem density over 10 cm tall between treatments were also not significantly different ($P = 0.1769$). However, a reduction in the density of red maple greater than 10 cm tall can be observed in the prescribed-burned and shelterwood-cut treatments in contrast to the control when comparing pre- and posttreatment means.

No significant differences in percent cover of herbs were found between treatments ($P = 0.0929$) (fig. 3). Mean herb cover of sampling plots ranged from 2.29 to 8.30 percent. Similarly, no significant differences were detected in the number of herbaceous species per plot between treatments ($P = 0.1774$). No new exotic plants were found. However, two new species colonized some of the treatment areas. Pokeweed-(*Phytolacca americana*) colonized areas where the soil had been disturbed by logging machines and fireweed (*Erechtites hieracifolia*) primarily colonized cells that were prescribed burned, though some individuals also appeared in the shelterwood-treatment cells.

SUMMARY AND CONCLUSIONS

The first objective of the research was to evaluate and compare the effectiveness of the shelterwood harvests and wildlife thinnings in terms of their ability to increase the success of oak regeneration. It was difficult to detect significant differences in the density of oak regeneration due to high variability in the distribution of oak stems within and between stands. In addition, the short period of time between treatment installation and measurement of the stands makes it difficult to arrive at definitive conclusions. However, patterns can be detected, and both treatments reduced the number of oak stems over 10 cm tall and generally increased the number of oak stems under 10 cm tall. Individuals in the 10-cm and taller size class were top-killed by fire and cutting, and sprouts from these individuals

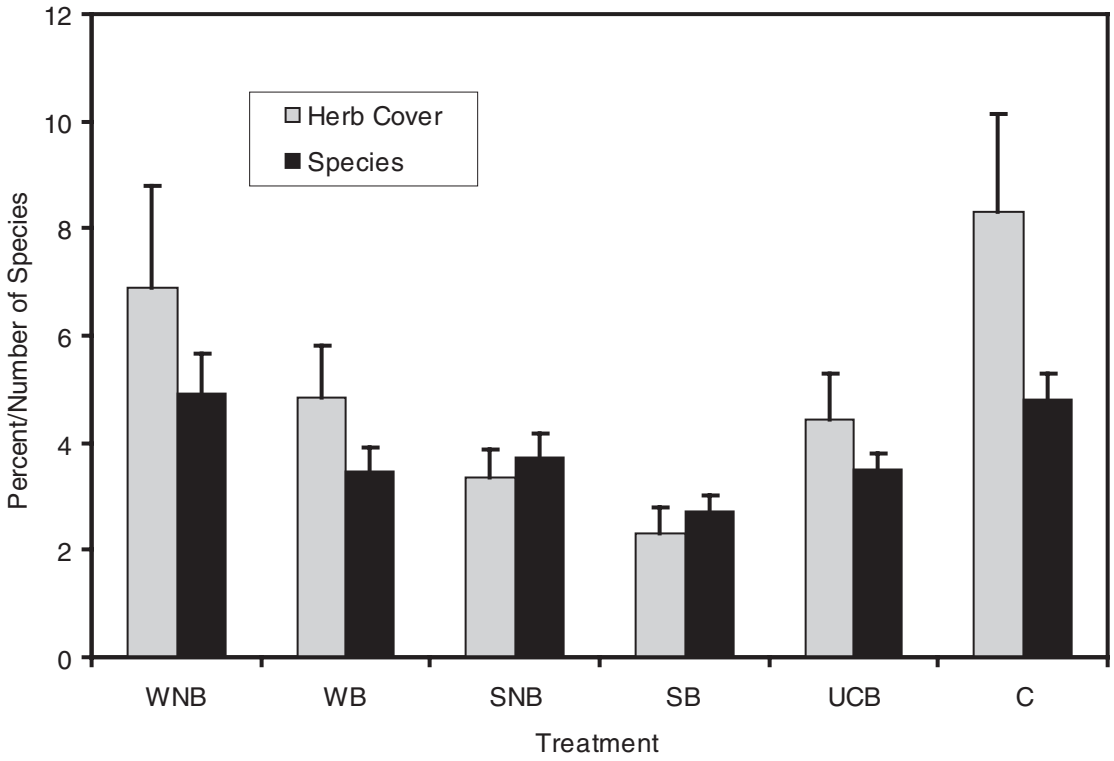

Figure 3—Percent cover of herbs and number of herb species per measurement plot by treatment. Error bars, significant differences, and treatment codes as in figure 1.

entered the smaller size class, leading to an increase in stems under 10 cm tall without any new seedling establishment. One exception was the increase in the density of white oak stems under 10 cm tall in the wildlife thinning combined with prescribed burning treatment. There was a greater increase in the smaller size class than can be accounted for by the decrease in the 10-cm and taller size class, suggesting a flush of new seedling establishment. Both of the treatments significantly increased understory light availability by reducing canopy cover. Increased light availability has been demonstrated to increase the growth and survival of oak regeneration (e.g., Beck 1970, Buckley and others 1998). The wildlife thinning treatments increased light availability relative to the uncut areas but not as substantially as the shelterwood cutting. Overstory removal by either method significantly increased PAR availability. In contrast, none of the treatments significantly affected measured soil-moisture levels. It is possible that other site factors (e.g., subsurface hydrology) not measured in this study played a more important role in influencing soil moisture than the treatments.

Prescribed burning significantly affected the distribution of oak regeneration over size classes. Oaks in the large seedling class, those over 10 cm tall but less than 140 cm tall, were significantly reduced due to top-killing by the fires. Stems less than 10 cm tall were significantly increased with burning. This increase in oak stems can be attributed to two sources: some new seedling establishment (white oaks) and new oak sprouts from oak regeneration that was top killed in the fire. The prescribed burned wildlife thinning treatment exhibited greater PAR levels than the unburned wildlife thinning. When combined with the wildlife thinning treatment, burning further reduced the midstory structure to allow more light to reach the seedling level. White oak stem density less than 10 cm tall significantly increased with wildlife thinning combined with prescribed fire. Thus, prescribed fire enhanced the effects of the wildlife thinning.

Both overstory removal treatments and prescribed burning had mixed results on woody competitors of oak. Prescribed burning likely increased competition between oaks and yellow-poplar and sassafras. However, prescribed fire reduced competition from red maple in all regeneration-size classes. The increase in yellow-poplar and sassafras likely occurred from seed already in the soil prior to the treatments and from sprouting. Prescribed burning, combined with overstory removal, provided the seedbed and increase in light necessary for germination and sprouting. We believe subsequent fires may be needed on a fairly frequent interval to reduce the number of yellow-poplar and sassafras stems. Provided there is a sufficient fuel load, burning can be carried out on intervals as little as every 2 to 3 years to reduce competition while not harming the oak stems. Subsequent fires should reduce the ratio of these competitors to oaks. An alternative would be to wait 3 to 5 years for these competitors to develop before burning, as outlined in the shelterwood-burn technique recommended by Brose and others (1999). Completion of the shelterwood-burn treatment in 2005 will allow comparison of the effects of fire in the first growing season and 4 years after shelterwood cutting on the sites.

Based on their effects on PAR and certain competitors such as red maple, shelterwood cuts, wildlife thinnings, and prescribed fire should benefit oak regeneration on the study sites. Long-term monitoring of the development of oak and potential competitors on the sites is necessary and planned.

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MODELING 9-YEAR SURVIVAL OF OAK ADVANCE REGENERATION UNDER SHELTERWOOD OVERSTORIES

Martin A. Spetich and David L. Graney[1]

Abstract—Survival of white oak (*Quercus alba* L.), northern red oak (*Q. rubra* L.), and black oak (*Q. velutina* Lam.) on upland oak stands was modeled 9 years after shelterwood treatment. Stands represented a range of site quality, overstory stocking, and understory treatments. There were three levels of understory treatment and two levels of shelterwood treatment for a total of six overstory-understory treatment combinations. Understory treatment consisted of (1) removal of all competing woody stems < 1.6 inches diameter at breast height, (2) removal of this diameter range of stems but only those that were ≥ 5 feet tall, and (3) no understory treatment. Overstory shelterwood treatments were 40 and 60 percent residual stocking. We used logistic regression to model survival of advance regeneration 9 years after understory and overstory treatments. Results were expressed as survival probabilities. Significant predictors of survival included initial seedling basal diameter, percent residual stocking of the shelterwood treatment, site index, and the number of terminal bud scale scars of the seedling prior to treatment.

INTRODUCTION

Upland hardwood stands in the Boston Mountains of northern Arkansas can have more than 1,000 stems per acre of oak advance reproduction (Graney 1989), but most stems are < 1 foot tall. Many of these stands are mature and fully stocked and have well-developed understories of shade-tolerant species. Given the size and status of existing reproduction, new stands that develop after a harvest often contain a low proportion of oaks. To help restore oak to this ecosystem, stimulating the survival and growth of this small advance reproduction is often a priority of forest management plans in the Ozark Highlands.

Oaks are important to wildlife and, in turn, to forest energetics. Wildlife species that utilize oak mast include white-tailed deer (*Odocoileus virginianus*); black bear (*Ursus americanus*); turkey (*Meleagris gallopavo*); blue jays (*Cyanocitta cristata*); squirrels (*Tamiasciurus* spp., *Sciurus* spp., and others); and mice (*Peromyscus* spp.). For instance, a study by Harlow (1975) found that acorns made up an average of 76 percent of the diet of white-tailed deer during November and early December. Fluctuations in wildlife populations often follow fluctuations in oak mast production (McShea and Schwede 1993, Nixon and others 1975, Wentworth and others 1990). Major declines in oak populations could also lead to declines in the populations of associated wildlife species where alternative resources are not available.

In this study, we introduce the use of the number of terminal bud scale scars as one predictor of survival of oak advance reproduction. Terminal bud scale scars are formed during a shoot resting phase that occurs after the first flush of shoot growth. Under good growing conditions, such as direct sunlight and frequent rainfall, a second flush of growth would begin from this bud (Johnson and others 2002). However, under the typically dense forest canopies and normally hot and dry summers of the Boston Mountains, there is rarely more than one flush each year.

Understanding how to predict successful survival of oak advance regeneration will allow managers to more effectively restore this valuable resource to the landscape. The objectives of this paper are to (1) identify predictors of survival of oak advance reproduction during the first 9 years under shelterwood conditions, and (2) provide survival models based on this information.

STUDY SITES

The study sites were located in the Boston Mountains of Arkansas, part of the southern lobe of the central hardwood region (Merritt 1980). The Boston Mountains are the highest and most southern feature of the Ozark Plateau Physiographic Province. They form a band 30 to 40 miles wide and 200 miles long from north-central Arkansas westward into eastern Oklahoma. Elevations range from about 900 feet in the valley bottoms to 2,500 feet at the highest point. The plateau is sharply dissected. Most ridges are flat to gently rolling and generally < 0.5 mile wide. Mountainsides consist of alternating steep simple slopes and gently sloping benches. Vegetation across the landscape is a forest matrix with inclusions of nonforest. Soils on mountaintops and slopes usually have shallow to medium depth and are represented by medium-textured members of the Hartsells, Linker, and Enders series (Typic Hapludults) derived from sandstone or shale residuum. Their productivity is medium to low. In contrast, soils on mountain benches are deep, well-drained members of the Nella and Leesburg series (Typic Paleudults). They developed from sandstone and shale colluvium, and their productivity is medium to high. Rocks in the area are alternating horizontal beds of Pennsylvanian shales and sandstones. Annual precipitation averages 46 to 48 inches, and March, April, and May are the wettest months. Extended summer dry periods are common, and autumn is usually dry. The frost-free period is normally 180 to 200 days long.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

METHODS

Treatments

Six mature upland hardwood stands were selected for study at three locations in the Ozark National Forest. Three stands are on upper north- or east-facing slopes with site indices of 57 to 63 feet (mean = 60 feet) for northern red oak (*Quercus rubra* L.), base age 50 years. The other three stands are on north- or east-facing mountain benches with northern red oak site indices of 72 to 80 feet (mean = 75 feet). Mean age for upper slope stands was 74 years (range = 72 to 84 years), while stands on mountain benches averaged 78 years (range = 70 to 84). Six plots (approximately 1 acre in area) were established in each stand. Overstory [stems ≥ 1.6 inches in diameter at breast height (d.b.h.)] densities were reduced to either 40 or 60 percent relative stocking density (Gingrich 1967). There were three levels of understory (stems < 1.6 inches d.b.h.) treatment: (1) removal of all competing woody stems < 1.6 inches d.b.h (intensive), (2) removal of this diameter range of stems but only those ≥ 5 feet tall (partial), and (3) no understory treatment. The six overstory-understory treatment combinations were randomly assigned to each plot.

Pretreatment overstory stocking for all plots averaged 106 percent, and basal area averaged 118 square feet per acre. The shelterwood was created by a low thinning (thinning from below). After all subcanopy stems < 1.6 inches d.b.h. were removed, the overstory canopy was harvested to the prescribed stocking level. Stumps of all slow-growing or noncommercial overstory stems were sprayed with 2,4-D plus picloram to reduce sprouting. Overstories on all plots were predominantly oak. Northern red, black (*Q. velutina* Lam.), and white oak (*Q. alba* L.) accounted for 80 percent of the overstory stocking before treatment and > 90 percent after treatment. White ash (*Fraxinus americana* L.) and black cherry (*Prunus serotina* Ehrh.) represented < 1 percent of the stocking on all plots.

Understory control treatments were imposed by cutting target stems near ground level and spraying stumps with the 2,4-D plus picloram herbicide immediately after cutting. Understory treatments were completed in May 1980, and overstories were cut May through July 1980. Understories on upper slope sites (site index 60 feet at 50 years) were dense mixtures of tolerant species such as red maple (*Acer rubrum* L.), serviceberry [*Amelanchier arborea* (Michx. F.) Fern], redbud (*Cercis canadensis* L.), and blackgum (*Nyssa sylvatica* Marsh.). Dogwood (*Cornus florida* L.), hophornbeam [*Ostrya virginiana* (Mill.) K. Koch.], pawpaw [*Asimina triloba* (L.) Dunal], and sugar maple (*A. saccharum* Marsh.) were common on bench sites (site index 75 at 50 years).

Reproduction Measurement

Reproduction was measured on a series of sixteen 1/735-acre subplots systematically distributed across the interior 0.25 acre of each plot. On each subplot, all reproduction < 1.5 inches d.b.h. was tallied by species and 1-foot height classes. In addition, all oak stems were identified and mapped for remeasurement. For these stems, basal diameter (1 inch above groundline) and height were measured to the nearest 0.1 inch and 0.1 foot, respectively. Reproduction was measured before treatment and 9 years after treatment. During the initial pretreatment measurement, the total number of terminal bud scale scars was counted for each stem of advance oak reproduction.

Analysis

Logistic regression was used to model survival of advance regeneration 9 years after understory and overstory treatments. Results are expressed as the probability of survival of advance regeneration. The full power and versatility of logistic regression to analyze dichotomous data first gained recognition in the 1960s (Hosmer and Lemeshow 1989). Since then researchers have utilized this method to examine everything from human health issues to the growth and survival of naturally regenerated trees (Lowell and others 1987). Here we use logistic regression to examine survival of advance oak regeneration.

To evaluate logistic regression model performance, we selected predictors with a *P* value of 0.05 or less based on the chi-square distribution with one degree of freedom. We used the Hosmer-Lemeshow goodness-of-fit statistic (Hosmer and Lemeshow 1989 to test the null hypothesis that the equation described the data. For Hosmer-Lemeshow goodness-of-fit, the null hypothesis was rejected for *P* values of 0.05 or less (indicating a poor fit of the equation to our data). It is therefore important to note that predictor *P* values of 0.05 or less have a different interpretation than the Hosmer-Lemeshow goodness-of-fit *P* values of 0.05 or less.

RESULTS AND DISCUSSION

Overall, significant predictors of survival included initial seedling basal diameter, percent residual stocking of the shelterwood treatment, site index, and the number of terminal bud scale scars of the seedling prior to treatment. Initial seedling height class was not a significant predictor. This was likely due to > 93 percent of seedlings being < 1 foot tall (the shortest height class in this study) at the beginning of the study (table 1). Only 69.4 percent of the reproduction was in the smallest (1-inch) basal diameter class (table 1).

We identified predictors of survival of advance reproduction for northern red oak, white oak, and black oak. For northern red oak, both number of terminal bud scale scars prior to treatment and site index were significant predictors

Table 1—Percent of advance regeneration by height and basal diameter class in upland hardwood stands of the Boston Mountains prior to treatment

Height		Diameter	
class		*class*	
feet	*percent*	*inches*	*percent*
< 1	93.3	0.1	69.4
2	4.9	0.2	14.8
3	0.9	0.3	8.7
4	0.6	0.4	3.1
5	0.3	0.5	1.7
> 5	0.0	> 0.5	2.4

of survival (tables 2 and 3). Survival probability of northern red oak increased as the number of terminal bud scale scars increased and as site index decreased (fig. 1). Similar relationships of increasing regeneration success with decreasing site index have been observed (Loftis 1990, Spetich and others 2002). To our knowledge, this is the first time that terminal bud scale scars have been used as an indicator of regeneration survival in oaks. However, number of terminal bud scale scars may not be a useful indicator on sites where deer browsing, frequent fire, or mechanical damage would result in frequent top-stem loss and resprouting.

One reason for the greater survival with increasing number of terminal bud scale scars may be related to its relationship to an ever-increasing root system. After each growth flush, photosynthates are translocated to the root system (Johnson and others 2002). Because each terminal bud scale scar represents one flush of growth, a larger number of terminal bud scale scars likely represents a relatively greater accumulation of photosynthate in that root system.

In dense stands of northern Arkansas, top dieback from fire was likely a rare occurrence over most of the past century. For instance, Guyette and Spetich (2003) found a mean fire-return interval (average fire-free interval) of > 80

Table 2—Survival probability logistic regression models for northern red, white, and black oaks[a]

Species	N	Model[b]	Figure
			no.
NRO	1,288	P_{REO}=1/(1+EXP(-(-1.22 + (0.203 * no. bud scale scars) + (3184.11 * (1/SI)^2))))	1
BO			
Model 1	550	P_{BLO1} = 1/(1+EXP(-(-0.669 + (0.264 * no. bud scale scars) - (0.056 * D))))	2
Model 2	550	P_{BLO2} = 1/(1+EXP(- (-1.284 + (16.359 * stem diameter) - (0.599 * D))))	3
WO	625	P_{WHO} =1/(1+EXP(-(-1.285 + (0.199 * no. bud scale scars) + (0.507 * D)))	4

NRO = northern red oaks; BO = black oaks; WO = white oaks.

[a] This is the probability of advance regeneration surviving 9 years under a shelterwood. See table 3 for associated *p*-values and parameter estimates.

[b] Model parameter definitions: no. bud scale scars = number of terminal bud scale scars on a seedling prior to treatments; SI = site index in feet at base age 50 years; D = parameter estimate for stocking density (see table 3); stem diameter = stem diameter prior to treatments.

Table 3—*P*-values and parameter estimates for survival models in table 2

	Goodness of-fit[a]	Percent stocking parameter estimates[b]		Logistic regression predictor *p*-values[c]			Stem
Species	*p*-value	40	60	Bud scale scars	D[d]	*(1/SI)^2*[e]	diameter[f]
NRO	0.418			< 0.001		0.033	
BO							
Model 1	0.311	0	1	< 0.001	0.019		
Model 2	0.579	0	1		0.004		< 0.001
WO	0.685	0	1	< 0.001	0.006		

NRO = northern red oaks; BO = black oaks; WO = white oaks.

[a] Based on the Hosmer-Lemeshow goodness-of-fit statistic, differences between estimated probabilities and observed responses are not significant (Hosmer and Lemshow 1989). Small *p*-values designate a poor fit of the equation to the data while large values (> 0.2) indicate a good fit.

[b] 40 = 40 percent residual shelterwood stocking; 60 = 60 percent residual shelterwood stocking.

[c] Based on the chi-square distribution with one degree of freedom.

[d] D = parameter estimate for stocking density.

[e] SI = site index, base age 50.

[f] Basal stem diameter prior to treatment measured at 1 inch above groundline.

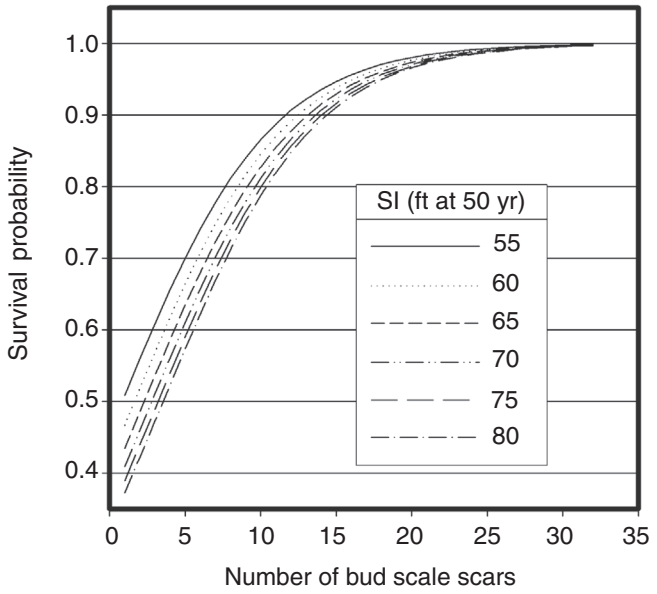

Figure 1—Northern red oak survival probability of advance regeneration by number of terminal bud scale scars prior to treatment and site index.

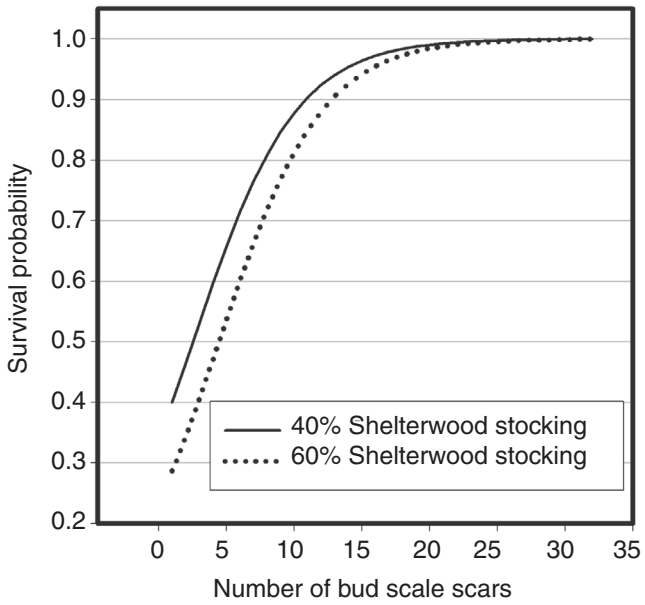

Figure 2—Black oak survival probability of advance regeneration by number of terminal bud scale scars prior to treatment and percent residual shelterwood stocking.

years for the time period from 1911 to 2000 in the lower Boston Mountains of Arkansas. Additionally, we rarely observed oak-specific mechanical damage from deer in this forest matrix. This was probably due to the preponderance of other species preferred by deer, such as poison ivy (*Toxicodendron radicans* L.); greenbrier (*Smilax Bona-nox* L., *S. glauca* Walt., *S. rotundifolia* L.); huckleberry (*Vaccinium vacillans* var. *crinitum* Fern.); red maple (*A. rubrum* L.); and Virginia creeper (*Parthenocissus quinquefolia* L. Planch.).

We produced two survival models for black oak advance reproduction. In model 1, significant predictors of survival included number of terminal bud scale scars and shelterwood percent stocking (tables 2 and 3). Survival probability increased with increasing number of terminal bud scale scars and as residual shelterwood stocking percent decreased (fig. 2). In model 2, significant predictors included initial basal stem diameter and percent shelterwood stocking (tables 2 and 3). In this case, survival probability increased as initial basal stem diameter increased but increased only slightly as percent shelterwood stocking decreased (fig. 3). Survival probability was nearly 100 percent for regeneration with an initial basal stem diameter of 0.4 inch for both the 40 and 60 percent stocking treatments. The importance of stem diameter and percent stocking were also noted in a recent paper examining the success of underplanted northern red oak (Spetich and others 2002).

For white oak advance reproduction, significant predictors of survival included number of terminal bud scale scars and shelterwood percent stocking (tables 2 and 3). Probability of survival increased with increasing number of bud scale scars and with increasing percent residual stocking (fig. 4). Survival increased with greater percent stocking and was the opposite of what we observed for black oak in this study. This is also contrary to findings of a study examining planted northern red oak (Spetich and others 2002).

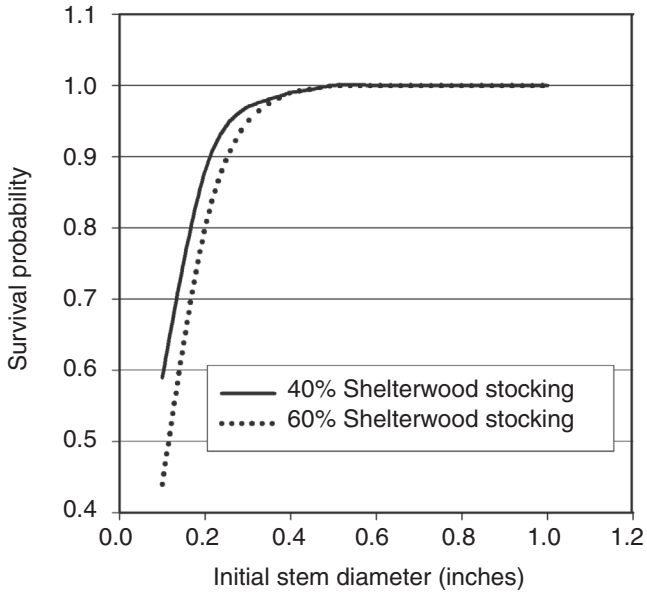

Figure 3—Black oak survival probability of advance regeneration by initial stem diameter prior to treatment and percent residual shelterwood stocking.

This increasing survival with greater stocking might indicate greater sensitivity of white oak to logging disturbance. For instance, as residual stocking level was decreased, relatively more trees were removed in the harvest, likely resulting in greater mechanical disturbance to the site.

When managing for both black oak and white oak, it may be useful to use an intermediate residual stocking level. Our models indicated somewhat higher survival for northern red oak at 40 percent residual stocking, while for white oak

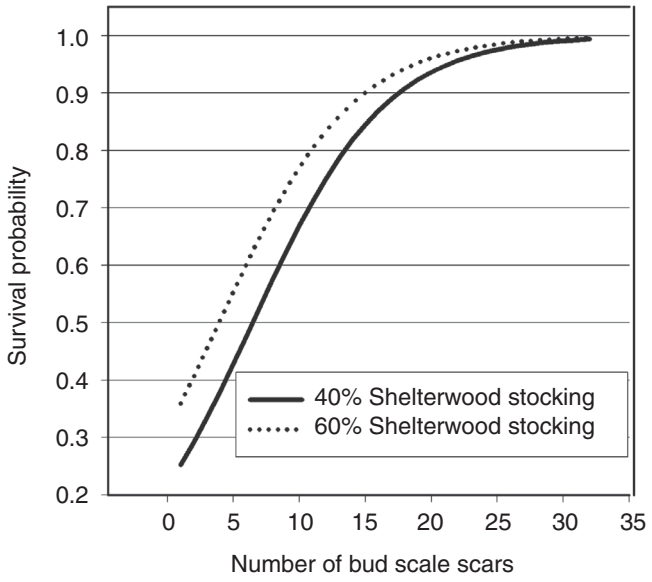

Figure 4—White oak survival probability of advance regeneration by number of terminal bud scale scars prior to treatment and percent residual shelterwood stocking.

the 60 percent stocking level indicated somewhat higher survival. On sites where advance regeneration of both black and white oak are equal, a residual stocking level of 50 percent may give better combined results for these two species. However, if the management objective is to increase the survival of one of the two species due to adequate regeneration of the other, then we suggest applying the residual stocking level that best suits that species.

ACKNOWLEDGMENTS

We extend our appreciation to the field technicians who installed and measured this study: Richard Chaney, Jim Whiteside, Greg Polus, Arvie Heydenriech, Jesse Swaford, and Kenny King. We thank Ozark National Forest personnel for assistance with stand selection and study installation. Thanks to Michael Shelton and Eric Heitzman for reviewing this manuscript and to Betsy Spetich for editorial guidance.

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TOPOGRAPHIC POSITION AND SITE INDEX: AN OAK REGENERATION RELATIONSHIP

David I. Shostak, Edward F. Loewenstein, and Mark R. Dubois[1]

Abstract—In 1996, a 10-year study was initiated in an upland hardwood forest in northern Alabama to assess establishment success and stocking levels of oak reproduction following three regeneration treatments: block clearcutting, strip clearcutting, and deferment cutting. Each treatment was applied to two 4-acre stands. In addition, two 2-acre uncut controls were monitored. All treatments were established on a north aspect with slopes ranging from 5 to 60 percent. Oak site index (base age 50 years) ranged from 64 feet on the upper slope positions to 88 feet on the lower slope positions. Data on operational and environmental variables were collected pre- and postharvest and analyzed to determine whether relationships exist with stocking or success of oak reproduction. Four growing seasons after the harvest, a relationship between topographic position, site index, and oak reproduction success was evident. Nonovertopped oak reproduction was found to be most abundant on the upper slope positions and least abundant on the lower slope positions, regardless of harvesting treatment.

INTRODUCTION

Oak regeneration has been a topic of much debate and continued study. Relationships ranging from the size and amount of advance regeneration, as well as specific site conditions to survival and success, continue to be researched. The findings from various studies generally show that large numbers of adequate advance regeneration are needed to maintain oak as a major component of future forests. Additionally, and maybe more importantly, is the finding that a topographic trend for oak regeneration success exists. Oaks have been found to compete better on upper slope positions that exhibit low to moderate oak site indices. Much of this research has been accomplished in areas like the Southern Appalachians and the Missouri Ozarks (Johnson 1993, Loftis 1993).

Within Alabama, oak-hickory forests make up approximately 35 percent (7.7 million acres) of the timberland with 65 percent of the oak-hickory forests in the State found in north Alabama (McWilliams 1992). These upland sites exhibit the topographic trend of oak site indices with good-quality sites on the lower to middle slopes and poor- to moderate-quality sites on the upper slopes. These forested areas have long been viewed as valuable in economic and social terms. Unfortunately, the oaks in these stands are no longer self-replacing. Information on where to concentrate management efforts may be the only way to economically ensure the continued presence of oak in these forests. Additionally, confirming the generally accepted trends in oak silvics for the upland hardwood forests in northern Alabama allows for the legitimate application of research results between these locations.

In 1996, a 10-year study was initiated in an upland hardwood forest in the mountains of northern Alabama to assess establishment success and stocking levels of oak reproduction following three regeneration treatments: block clearcutting, strip clearcutting, and deferment cutting. The purpose of this study was to determine which ecological factors had an effect on fourth-year postharvest stand composition and to investigate whether the applied silvicultural methods developed adequate oak reproduction. The topographic trends based on data collected after the fourth full growing season (Fall 2000) are reported in this paper. The specific objectives of this assessment were to (1a) determine which potential environmental factors have affected successful fourth-year postharvest oak stocking, (1b) determine which potential environmental factors have affected fourth-year post-harvest oak stem success, and (2) investigate the contribution and competitiveness of oak stump sprouting 4 years after harvesting and compare the effect of the silvicultural treatments (block clearcutting, strip clearcutting, and deferment cutting) on oak reproduction.

METHODS

Study Site

The study was established on north-facing slopes in Alabama's Cumberland Mountain-Plateau Region. It is located on the Yeager Demonstration Forest presently owned and managed by International Paper Corp. This demonstration forest can be found in the southeast portion of Lawrence County, AL, adjacent to the William B. Bankhead National Forest.

Major ridges typically run east to west with slopes ranging from 5 to 60 percent. Oak site index (base age 50 years) was found to be 64 feet on the upper slope positions and 88 feet on the lower slope positions. Major hardwood species consisted of oaks (Q*uercus* spp.), hickories (C*arya* spp.), sugar maple (*Acer sacharum*), yellow-poplar (*Liriodendron tulipifera*), ash (*Draxinus* spp.), and sweetgum (*Liquidambar styraciflua*).

Study Design

Each regeneration treatment was randomly assigned to two 4-acre stands (400 by 440 feet). Two 2-acre (200 by 440 feet) uncut controls were also established. The treat-

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

ment areas and the controls were oriented south to north along the gradient (slope). Three transects or plot lines were established within each treatment area, whereas one transect was established within each of the control areas. Each line of plots was comprised of approximately 67 one-half chain (33 feet) segments made up of 5-milacre plots (6.6 feet by 6.6 feet) running west to east. The odd numbered measurement plots along the central line were used to tag seedlings and complete an overall inventory including stems of all sizes. Stump sprouts and over-story data were collected in every plot in the one-half-chain-wide segment. This setup allowed for ease of relocation and tagging of seedlings, saplings, and residual overstory trees. Additionally, environmental data on each plot was collected consisting of various classes of vegetative competition cover, woody debris per plot, and topographic position. The approximate total number of milacre plots per transect is 334, with a total of 20 lines in the 8 blocks of this study.

Data Collection

Advance reproduction, overstory, and environmental data were collected during the summer of 1996 prior to harvesting. Immediately following the harvest in the fall of 1996, site and soil impacts were assessed and recorded for each measurement plot as well as a detailed regeneration and overstory survey. Additionally, 15 months after harvesting (Fall 1997), the stand was re-entered, plots relocated, and remeasured. The fifteen-month data is not reported in this paper. Finally, in the fall of 2000, after four full growing seasons, a regeneration and overstory survey was once again conducted. Postharvest germination was measured, tagged, and recorded. All reproduction was classified by competitive position: free to grow (FTG), crowded but not overtopped (CR), or overtopped (O). These classes were modified from Smith (1986).

Data Analysis

The variables examined for the fourth-year oak reproduction assessment fell into two categories, ecological factors and silvicultural factors. The ecological factors consisted of advance reproduction (numbers and sizes) topographic position, post- harvest establishment (numbers and sizes), postharvest seedling/sapling competitive position, percent cover of undesirable species and other nonoak tree species, percent cover of woody debris, and degree of disturbance. The silvicultural factors were: block clearcutting, strip clearcutting, and deferment cutting.

Most of the relationships found with the various ecological factors can be associated with their topographic position and related site index. Additionally, significant differences were found between regeneration treatments. However, the topographic trends were still evident across all treatments. Stepwise multiple logistic regressions were used to determine the models that best fit the data. All explanatory variables were entered into the model in various forms, combinations, and transformations. Multiple criteria for model fit were examined to determine the best models for plot stocking, individual stem success, and sprouting success.

Stepwise logistic regression using the Logistic Procedure in the Statistical Analysis System (SAS) for Windows, release 6.12 (SAS Institute Inc. 1990a, 1990b, 1997) was employed. The stepwise logistic regression procedure was used to explore a data set of explanatory variables thought to be related to the outcome variable. During the stepwise procedure, a statistical algorithm checked the importance of these variables and determined the addition or deletion of these variables into the model. The importance of an individual variable was defined as a measure of the statistical significance of the coefficient of the variable (Devore 1995, Hosmer and Lemeshow 1989). According to Hosmer and Lemeshow (1989) this procedure offers a useful and effective data analysis tool when the outcome being studied is relatively new, and those covariates and their associations with the outcome are not well understood. Stepwise logistic regression offers a fast and effective way to screen large numbers of variables and to simultaneously fit a number of logistic regression equations. One caution with logistic regression: As with any model-building technique, you are trying to find the best fitting and most parsimonious, yet biologically reasonable model to describe the relationship between an outcome and a set of independent variables (Hosmer and Lemeshow 1989). Although in most situations the stepwise method will identify a good model, there is no guarantee that the best model or a nearly best model will result. In certain situations where there appears to be a strong relationships among potential predictors, careful scrutiny is advised (Devore 1995).

Since the nature of this study is one of exploration, and the goal was to detect the influences affecting oak reproduction in a North Alabama upland hardwood forest, stepwise logistic regression seemed fitting. Furthermore, examining the site conditions and harvesting activities on such a site has previously not been well-documented. Using this type of exploratory analysis will bring about a better understanding of the natural processes. Logistic regression is also the preferred method when the outcome variable is a binary or dichotomous variable, such as success or milacre plot stocking (Hosmer and Lemeshow 1989).

When using stepwise regression for exploratory purposes it is important to choose an appropriate α level to judge the importance of variables. Hosmer and Lemeshow (1989) state that the use of an $\alpha = 0.05$ for entry into the model is too stringent and may often exclude important variables from the final model. Choosing an α level of 0.25 might be reasonable when the goal of the analysis is broad and the intent is to provide a more complete picture of the variables. For this study, a second α level of 0.15 was chosen, which indicated a minimal level for a variable to remain in the model. Essentially a variable will enter the model if it is deemed significant at an α of 0.25, and a variable will be deleted from the model if it is not significant at an α of 0.15 (Rao 1998).

In order to determine the model that best fits the data, various criteria for assessing fit were examined. The Akaike Information Criterion (AIC) and the Schwartz Criterion (SC) were both used to compare different models fitted to the same data with lower values for each indicating a better model (Younger 1998). The adjusted R^2 was also examined to determine the amount of variation attributed to the model. To assess the contribution of individual independent

variables to the model, an analysis of maximum likelihoods was used. To do this, standardized estimates and odds ratios were evaluated. Younger (1998) states that the true value in assessing standardized estimates in the relative affects of multiple independent variables on the response is when these independent variables have different units of measurement, whereas the odds ratio is a measure of association that approximates how much more likely or unlikely it is that an event will happen (Hosmer and Lemeshow 1989, Younger 1998).

The analysis of maximum likelihood estimates for individual oak stem success for topographic position were based on the upper slope positions being coded as the reference variable. So, all results demonstrate the relationship found between the middle slope and the reference variable as well as the lower slopes and the reference variable.

RESULTS

Prior to harvesting, the topographic trend was already evident among the advance reproduction of all species. Composition of nonoak commercial species or other commercial species was greatest on the lower slope positions, whereas oak composition was found to be greatest on the upper slope positions (table 1). This same trend was found 4 years after harvesting within in the seedling-sapling reproduction classes for overall and non overtopped reproduction (NOT; table 2). NOT reproduction was considered to be those stems in the FTG and CR classes. Oak reproduction maintained its higher numbers on the upper slope positions where competing commercial species were found to be at their lowest. Unexpectedly, other NOT commercial species followed the same pattern as oak reproduction. This inconsistency might be explained by a lower number of overall stems per acre on the upper slope positions, thus allowing greater numbers of all species to fall into the NOT category. Additionally, the greater presence of NOT commercial species other than oak was not of concern because they were still commercial species.

Milacre Oak Plot Stocking

The following model was chosen because it best represented the data and had the lowest AIC and SC as well as a high adjusted R^2.

$$F4QSTK = f\ (TRTMT, TOPO, S1QALLLG, ARCRUSH, COMPLOG). \quad (1)$$

where F4QSTK = fourth year nonovertopped oak milacre plot stocking, TRTMNT = regeneration treatment, TOPO = topographic position, S1QALLLG = preharvest oak stems per milacre plot greater than 12 inches in height, ARCRUSH

Table 1—Preharvest composition of advance reproduction (AR)[a] by topographic position

Species	Upper slope (121 plots)	Middle slope (190 plots)	Lower slope (177 plots)	Total
	stems per acre			
Oaks	5,752	1,874	1,011	8,637
Other commercial	7,860	10,547	17,333	35,740
Noncommercial	1,008	689	1,689	3,386
Overall	14,620	13,110	20,034	47,764

[a] AR includes stems of any size including the sprouting potential of cut trees.

Table 2—Total fourth-year reproduction and nonovertopped reproduction (NOT) by topographic position

	Upper slope (121 plots)		Middle slope (190 plots)		Lower slope (177 plots)		Total	
Species	Total	NOT	Total	NOT	Total	NOT	Total	NOT
	stems per acre							
Oaks	2,851	347	1,105	94	571	62	4,527	503
Other commercial	6,678	2,727	9,737	2,447	11,379	2,249	27,794	7,423
Noncommercial	1,165	612	900	374	1,672	780	3,737	1,766
Overall	10,694	3,686	11,742	2,821	13,621	3,091	36,057	9,604

NOT = nonovertopped reproduction.

= fourth year percent competition of *Rubus* spp. and shrubby vegetation per milacre plot with an arc-sin square root transformation, and COMPLOG = preharvest percent competition of nontree vegetation per milacre plot with a log transformation.

This final model was considered significant (p = 0.0773) for the chosen α levels. The Hosmer and Lemeshow (1989) goodness-of-fit statistic (10.44 with 8 DF; p = 0.2355) was determined to be nonsignificant; thus, the hypothesis of goodness-of-fit cannot be rejected. Additionally, an adjusted R^2 of 0.2116 indicated that approximately 21 percent of the variation was accounted for by the model.

The analysis of maximum likelihood estimates for the topographic position variable indicate that it was approximately 66 percent more likely for a milacre plot to be stocked with an oak 4 years after harvesting on the upper slope positions than either of the other topographic positions. This was represented by a negative standardized estimate for the middle slope (-0.111821) and lower slope (-0.097443) positions revealing a relatively weak effect of these variables to the model. Odds ratios were less than 1; the middle slopes were 0.659:1; and the lower slopes were 0.666:1. These ratios can also be stated as a percent likelihood by subtracting the odds from 1. Thus, milacre plot stocking would be 33.4 percent less likely on the lower slope positions and 34.1 percent less likely on the middle slope postions.

Given this greater likelihood for a plot to be stocked 4 years after harvesting on these upper slopes, it is important to look deeper into the dataset. Table 3 presents the plot-stocking data as well as changes in stocking from preharvest to year 4. Initially and at year 4, the upper slope positions had greater plot stocking. Additionally, milacre plot stocking on the upper-slope positions decreased by 15 percent less than the other positions.

Individual Oak Stem Success

This final model for oak stem success exhibited the lowest AIC and SC and had a relatively high adjusted R^2. It was also determined that this model best represented the data.

F4QSUC = f (INSZ, TRMT, TOPO, SHRBLOG). (2)

where F4QSUC = fourth year individual stem success, INSZ = initial stem size measurement categories, TRTMT = regeneration treatment, TOPO = topographic position, and SHRBLOG = fourth year percent competition of shrub species per milacre plot where a successful oak stem was found with a log transformation. This final model was significant at a chi-square probability of 0.7215 for the chosen levels. The Hosmer and Lemeshow (1989) goodness-of-fit statistic was 6.4317 with 8 DF (p = 0.5990), which was non-significant. Thus, the hypothesis of goodness-of-fit cannot be rejected. An adjusted R^2 of 0.0922 indicated that approximately 9 percent of the variation is accounted for by the model. Since the nature of this study is one of exploration, a low adjusted R^2 was acceptable. Furthermore, the high degree of variability in natural systems and the unpredictable nature of the parameters in this study allowed for a low adjusted R^2.

It was 80 percent less likely that an individual oak stem would be successful on the upper slope positions than the lower slope positions and 64.5 percent less likely that a stem would be successful on the upper slope than the middle slope positions, according to the analysis of maximum likelihood estimates. At first glance this seemd to go against conventional thinking as oaks generally do better on poorer quality upper slope positions. This issue will be addressed shortly. Standardized estimates of 0.037252 for the lower slope positions and 0.075621 revealed a relatively moderate effect of topographic position variable to the final model. Odds ratios were 1.2:1 for the lower slope positions and 1.355:1 for the middle slopes. Stated as percent likelihoods, it was 20 percent more likely that a stem would be successful on the lower slope, and 35.5 percent likely that a stem would be successful on the middle slope positions.

In order to understand the origin of the successful stems, these results were broken into advance reproduction and postharvest germination. Table 4 presents these results. Percent success of advance reproduction was higher on the middle slope and lower slope positions; however, actual

Table 3—Change in plot stocking of milacre plots for oaks from pre-harvest to fall 2000 by topographic position

Topographic position	Stocked preharvest[a]		Stocked Fall 2000[b]		Stocking change[c]	Change, as a percent of AR stocking[d]
	%	*no.*	%	*no.*	%	%
Upper slope	38	46	21	26	-7	-45
Middle slope	15	28	6	12	-9	-60
Lower slope	15	26	6	10	-9	-60
Overall	20	100	10	45	-10	-50

[a] Stocking of plots with at least one oak stem > 12 inches preharvest.
[b] Stocking of plots with at least one oak stem in a nonovertopped competitive position.
[c] As a proportion of total plots in the class.
[d] As a proportion of the plots that were stocked at preharvest.

Table 4—Success of oak advance reproduction and oak post harvest germination by topographic position 4 years after harvesting

Regeneration type	Topographic position							
	Upper slope		Middle slope		Lower slope		Overall	
	%	*no./ac*	%	*no./ac*	%	*no./ac*	%	*no./ac*
AR	3	165	4	74	4	40	3	84
PHG	8	182	2	21	4	23	5	61

AR = advance reproduction; PHG = post harvest germination.

successful stems per acre were highest on the upper slope positions, greater by more than 87 stems per acre than either of the other positions. In contrast, percent success of postharvest germination was greatest on the upper slope positions as were actual stems per acre—greater by more than 159 stems per acre.

Oak Stump Sprouting Success

The model that best represented the oak sprouting success data was:

SPRSUC = f (TMT TOPO DBHCL). (3)

where SPRSCU = fourth year sprout success, TRTMT = regeneration treatment, TOPO = topographic position, and DBHCL = parent tree diameter at breast height by 2-inch diameter classes. Even though the chosen model did not exhibit the lowest AIC or SC, it did exhibit the highest adjusted R^2. Additionally, there were no noteworthy differences in the strength of the parameter estimates or odds ratios between models. Furthermore, the model that had the lowest AIC and SC values contained only one independent variable, DBHCL.

The chosen model was highly significant at a chi-square probability of 0.0001 and the Hosmer and Lemeshow (1989) goodness-of-fit statistic (9.3583 with 8 DF; $p = 0.3130$), which is nonsignificant. Thus, the hypothesis of goodness-of-fit cannot be rejected. An adjusted R^2 of 0.1614 indicated that approximately 16 percent of the variation was accounted for by the model and was considered acceptable.

The analysis of maximum likelihood estimates for this model indicated that it was approximately 80 percent more likely for a sprout to be successful on the upper slope than either of the other slopes. Standardized estimates for topographic position indicated a relatively high contribution from this variable -0.0368633 for the lower slope positions and -0.067484 for the middle slope positions. Odds ratios indicated that it was 20.1 percent (0.799:1) less likely for a sprout to be successful on the lower slope positions, and 22.0 percent (0.780:1) less likely for a sprout to be successful on the middle slope positions. Actual numbers per acre and percent success of oak stump sprouts by topographic position can be found in table 5.

DISCUSSION

Oak reproduction, including sprouts, normally follows a topographic trend with oak success decreasing as site quality increases and topographic position nears the lower slopes (Auten and Plair 1949, McNabb 1992, Roach and Gingrich 1968, Sander and others 1984). The results found on this site can be considered a confirmation that site index could be used as a measure of site quality. Essentially, drier poorer quality upper slope positions tend to favor the drought and shade tolerances of the oaks rather than the more mesic nature of competing species (Smith 1993). All topographic positions on this site were considered “better” quality sites with oak site indices (base age 50 years) greater than 60. Lorimer (1993) reported that sites exhibiting an oak site index (base age 50 years) greater than 60 are likely to convert to a more mesic species composition. Thus any NOT oak reproduction on this site should be considered acceptable.

On this same site in north Alabama, Stockman (2001) and Golden and others (1999) found this same relationship early on when studying apparent first-year oak seedling survival and 15-month oak stocking. It was also determined that a large yellow poplar and sugar maple component, which had greater success rates on the lower slope and middle slope positions, would negatively influence oak reproduction; our data confirm this speculation.

Table 5—Success of oak stump sprouts by topographic position 4 years after harvesting

Regeneration type	Topographic position							
	Upper slope		Middle slope		Lower slope		Overall	
	%	*no./ac*	%	*no./ac*	%	*no./ac*	%	*no./ac*
Sprouting	20	19	17	9	12	2	18	9

The unexpected positive relationship associated with oak stem success was noteworthy. The higher percent success on the middle and lower slope positions seemed to go against conventional thinking and research. This can be explained by reviewing tables 1 and 2. The upper slope positions had a greater number of stems present preharvest, and density at this topographic position decreased by the largest factor by year 4. This large decrease was for NOT stems as well as all oak stems. This larger decrease on the upper slope positions corresponded to the smallest percent success, as seen on table 4. Even though the upper slope positions had the smallest percent success values, they still exhibited the greatest number of successful stems per acre. Thus, on an absolute basis, the generally accepted topographic trend held true.

CONCLUSIONS

Our assessment of oak milacre plot stocking, individual stem success, and successful stump sprouting agrees with contemporary literature. It also confirmed that large numbers of well-developed advance reproduction are needed to successfully reproduce oaks as a major component of a future stand no matter where they may happen to be growing (Golden and others 1999; Loftis 1990, 1993; Roach and Gingrich 1968; Sander and others 1984).

Management Implications

When managing for natural oak reproduction it is important to focus efforts where they may be the most successful. In looking at the results from this study in North Alabama, we can see that oak regeneration does well on the upper slope positions. Thus, it may not be the best use of resources to manage on these positions. Additionally, it may be too hard to successfully manage for oaks on the lower slope positions. Focusing mainly on the middle slope positions and tending the upper slope positions seems to be the best management advice that can come from this study.

ACKNOWLEDGMENTS

I would like to thank those that cooperated on this project: International Paper Corp., the USDA Forest Service, Southern Research Station, Andrews Forest Service Lab in Auburn, Alabama, and Auburn University's School of Forestry and Wildlife Sciences.

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A DECISION-MAKING MODEL FOR MANAGING OR REGENERATING SOUTHERN UPLAND HARDWOODS

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Abstract—A decision-making model for managing or regenerating southern upland hardwoods is being created for three physiographic provinces including the Cumberland Plateau, Western Highland Rim, and Upper Coastal Plain. The model performs a stand evaluation, from a silvicultural standpoint, and declares a stand as being either manageable or in need of regeneration. Model variables include species class, diameter, height, grade, vigor, crown class, and tree-preference class. Each of the variables is used to generate a stand-index value that must meet a predetermined cutoff value in order for a stand to be considered manageable. Any index value below the cutoff value will return a decision to regenerate the stand.

INTRODUCTION

A large number of species, long rotation age and a shortage of professional hardwood silviculturists combine to increase the difficulty of making hardwood management decisions. Evaluating hardwood stands requires appreciable knowledge and expertise in hardwood management. The initial decision is to determine if an existing stand is manageable or in need of regeneration. In pine management, a resource manager may have one or two species to be concerned with, whereas a hardwood manager must typically deal with multiple species. Hodges and Switzer (1979) noted the great diversity in species composition led to many of the silvicultural problems, which chiefly centered on the maintenance of desired species composition. According to Smith (1988), the cyclic nature of market values and popularity of certain woods made selecting a preferred species a questionable practice.

Long rotation age is another factor that increases the difficulty associated with hardwood management decisions. Rotation ages for sawtimber production generally range from 50 to 70 years, and if no management techniques are employed, rotations can run much longer. Long rotation age affects the decision process in that any stand decision may have to be dealt with for an extended period of time. For experienced hardwood professionals, making decisions on a stand's management potential is not usually difficult, especially when the stand has an extremely low or high management potential. Stands considered borderline in management status are generally the ones that create uncertainty. Furthermore, if the hardwood forester is not experienced, this decision may become difficult for any hardwood stand (Manuel 1992).

There are few hardwood models currently available to resource managers. Some of the models that do exist, such as SILVAH, base decisions on multi-resource attributes that emphasize timber production and wildlife, biodiversity, aesthetic, water, and environmental goals (Marquis and Stout 1992). These variables are certainly important; however, they can be extremely complex. Loftis and McGee (1993) stated that regeneration prediction models were lacking for many ecosystems where oaks are important and for regeneration techniques other than clearcutting. Belli and others (1999) proposed a hardwood regeneration model that suggested advance regeneration is the key to establishing less tolerant species on southern hardwood sites. Though some regeneration models do exist, there remain regeneration aspects to be modeled. Other models for upland hardwoods involve growth and yield. G-HAT, GROAK, TWIGS, and GROPOP are among the growth and yield models for upland hardwood stands. G-HAT is a computerized growth and yield model designed for thinned hardwood stands in the Blue Ridge Province in the Southern Appalachians (Harrison and others 1986). GROAK is a growth and yield model for upland oaks at the stand level, TWIGS is an individual tree-growth model for yellow poplar, and GROPOP is a stand level growth and yield model for yellow poplar (Perkey and Carvell 1988). The primary difficulty with hardwood growth and yield models is that they are site and species specific, which can limit their use.

Hardwood management and regeneration decisions begin with an evaluation of the present stand conditions. Manuel (1992) completed a management/regenerate decision-making model for bottomland hardwoods in the South. This model is based on establishing an index for stand conditions according to stocking levels of desirable species, tree-preference class, and individual tree characteristics. Under Manuel's system, a stand's index value must meet a cutoff index value, which is based on certain ownership objectives. The current study will draw from this idea and focus on upland hardwood sites in an attempt to complete the modeling of manage/regenerate decisions for southern hardwoods. The objectives of this study are (1) to produce a manage/regenerate decision-making model for southern upland hardwood stands that is based on a stand's management potential from a silvicultural standpoint and (2) to incorporate the model into a computer program that will be available to end users.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

METHODS AND MATERIALS

Study Sites

Three physiographic provinces are being modeled including the Cumberland Plateau, the Western Highland Rim, and the Upper Coastal Plain. The areas of interest within these sites involve high-quality hardwood sites capable of producing quality sawtimber products. Lower quality sites within these provinces may be more suitable for pine or hardwood pulpwood production. In general, the higher quality sites are on the mid- to lower slope topographic positions. It is the mid- to lower slopes that have been sampled for the model.

Field Procedures

A minimum of 12 half-acre (83.3 foot radius) plots have been established in each province. Each plot has been selected to represent a particular set of stand conditions. The variation in stand conditions is designed to express a range of management potential (from low to borderline to a high management potential). The variation in management potential is primarily adjusted by the stocking of desirable species and quality of the trees within the stand.

Each plot is established using a radius of 83.3 feet from plot center. Using a GPS unit, every plot is recorded by its latitude and longitude. Plot boundary lines have been flagged for recognition. Beginning from a north line, individual tree characteristics (species class, diameter, tree class, etc.) are recorded for each tree within the half-acre plot. Species, species class, diameter at breast height (d.b.h.), and tree class are recorded for all trees larger than 5 inches in d.b.h. Merchantable height, grade, vigor, and crown class are only recorded for trees greater than or equal to 12 inches in d.b.h.

Each plot is being evaluated by an expert panel consisting of nine members. The panel consists of corporate, government (State and Federal), and university hardwood professionals that have expertise in upland hardwood management. The panel will evaluate each stand and determine if it is either manageable or in need of regeneration for each management objective. The goal is to have the expert decisions coincide with the decisions of the model. The usefulness of the model will be gauged by the level of agreement between the hardwood professionals' decisions and the model's decisions.

Model Description

The model assigns points to individual tree characteristics and accumulates the points for each characteristic into a tree value. The individual tree values are accumulated into plot values, which are adjusted to overall stand values. The model includes a series of objectives that can be used to apply constraints to a given stand. The total value for a given stand is compared to the cutoff value for a given objective, and the model makes a decision to either manage or regenerate the stand in question. If the overall stand value exceeds the cutoff index value, the model returns a decision to manage the stand. Alternately, if the stand value is below the cutoff value, the model decision is to regenerate the stand.

The Function of Individual Tree Characteristics

Individual tree values are determined through point values assigned to individual tree characteristics. The tree characteristics are comprised of additive and multiplicative variables. The additive variables include species class, merchantable height, butt log grade, tree vigor, and crown class. The multiplicative variable for the model is tree class. The function of d.b.h. in the model is to provide a tree with its initial value (or maximum value). The sum of the additive tree characteristics equals 12 points, and the percent of the 12 possible points a tree receives is used to adjust the initial value of a given d.b.h. This adjusted tree value is then multiplied by a percent value for a particular tree class (such as a tree in the reserve tree class receives 75 percent of a given amount of possible points) to provide the tree with its final value (table 1).

Additive Variables

The additive variables used in the upland model include species class, crown class, butt log grade, merchantable height, and vigor. Each of these tree variables is assigned a rank and a point value for each rank. Species class and crown class may receive more points than merchantable height, vigor, and butt log grade (table 1). The total amount of points allowed for all individual tree characteristic variables combined is 12. The percentage of total points captured is calculated for the additive variables in each tree (i.e. 10 out of the 12 possible points equal 83.3 percent). The percent captured from the additive variables is then used to adjust a given tree value.

Table 1—Variables used in the upland decision-making model

Additive variables	Rating	Point value
Species class	Desirable	3
	Acceptable	0
Merchantable height	2.5 logs or higher	2
	1.5 to 2.0 logs	1.5
	1.0 log	1
Butt log grade	Grade 1	2
	Grade 2	1.5
	Grade 3	1
Vigor	High	2
	Medium	1.5
	Low	0.5
Crown class	Dominant/codominant	3
	Intermediate	1.5
	Suppressed	0.5
Multiplicative variable	**Rating**	**Percent**
Tree class	Preferred	100
	Reserve	75
	Cutting stock	-25
	Cull	-25

There are three possible ratings that can be assigned to species class, including “desirable”, “acceptable”, and “unacceptable”. The desirability for particular species has been established through a review of the literature and input from hardwood resource managers in the areas modeled. Furthermore, desirability levels for different species are designed to meet the ownership objectives, which relate to management goals, in the model. Desirable species are those that are considered suitable for the management objectives. For a species to be considered “desirable”, the species must be sufficient for a crop tree. In other words, a desirable species is appropriate for the management objectives and should be included in future stand management. Desirable species receive the highest points of the three species ratings (3.0 points) in the model. Acceptable species are those that are considered acceptable for the management of the current stand but would not be a desirable crop tree in future stands. Acceptable species do not add points to the additive value of a tree (0.0 points). Essentially, acceptable species have some value in the current market, but not enough to be involved in future stands. Unacceptable species would not be suitable crop trees nor would they be acceptable in the current stand. Unacceptable species have little to no market value and should not be a part of timber production management. Unacceptable species are simply classified as cutting stock trees and apply a negative value to the stand.

Crown class is a major individual tree characteristic in the model. The crown-class variable may receive up to 3 points in the model. Crown class is broken down into four categories: dominant, codominant, intermediate, and suppressed. Dominant and codominant crowns receive 3 points, intermediate crowns receive 1.5 points, and suppressed crowns receive 0.5 points.

The role of butt log grade in the model is to incorporate a variable that represents stem quality. There are three butt log grades that are assigned a value in the model. Grade one logs receive 2.0 points, grade two logs receive 1.5 points, and grade three logs receive 1.0 point. Trees that fall into the grade 4 category are assigned to the “cull” tree class; however, sound grade 4 trees are assigned to the “cutting- stock” class. The grades are based on the USDA Forest Service grading criteria (USDA Forest Service 1981). Smaller sawlog trees, trees from 12-to 14-inch d.b.h. classes, do not provide a proper scaling diameter by the grading criteria. Therefore, the smaller sawlog trees have been graded using a subjective analysis of the trees future potential.

Merchantable height is recorded in logs and half logs for trees equal to or larger than 16 inches in diameter. The 12- and 14-inch diameter trees generally receive 1 log. The minimum acceptable merchantable height in the model is 1 log (16 foot). Trees with a merchantable height of 2.5 or more logs receive 2.0 points in the model. Trees with a merchantable height from 1.5 to 2.0 logs are assigned 1.5 points, and trees with 1 log are assigned 1.0 point.

The vigor variable is evaluated on a subjective basis. Vigor estimations are based on a growing stock trees’ crown and trunk. The tree crowns are evaluated for fullness (relative to species) and presence of die-back (dying limbs). The trunks are evaluated by an estimation of growth rate and condition (damage or defect). The vigor class is incorporated to provide a value for overall tree health. There are three classes of vigor: high, medium, and low. High-vigor trees receive 2.0 points, medium-vigor trees receive 1.5 points, and low-vigor trees receive 0.5 points.

The Multiplicative Variable

The multiplicative variable, tree class, is one of the most important variables in the model. Each tree value is adjusted by its tree class to provide a final tree value. There are four categories of tree class including preferred, reserve, cutting stock, and cull (Putnam and others 1960). Preferred growing-stock trees are “crop trees” that will be managed throughout the entirety of the rotation. Therefore, preferred growing-stock trees receive 100 percent of their potential value. For example, a 20-inch preferred growing-stock tree (2.44 possible points) that captured 10 out of 12 points (83.3 percent) for individual tree characteristics contributes (2.44 * 0.833 * 1.0 = 2.03) 2.03 points to the plot value. Reserve stock trees are trees that are in good condition but do not qualify as preferred stock or may not be capable of remaining in the stand throughout the rotation (due to loss of vigor). Reserve growing-stock trees capture 75 percent of their potential value. For example, a 20-inch reserve growing-stock tree (2.44 possible points) that captured 10 out of 12 points (83.3 percent) for individual tree characteristics contributes (2.44 * 0.833 * 0.75 = 1.52) 1.52 points to the plot value. Cutting-stock trees are either of an unacceptable species or in risk of mortality within the next 10 years of management. Cutting-stock and cull trees apply a slightly negative value (-25 percent). For example, a 20-inch cutting-stock or cull tree (2.44 possible points) contributes (2.44 * (-0.25) = -0.61) -0.61 points to the plot value.

Role of Management Objectives

The upland hardwood decision-making model employs a variety of management objectives, which assist in making a resource manager’s decisions meet the desired goals. The primary variables that can be adjusted in the model are (1) the acceptability of yellow poplar and sugar maple and (2) whether a 20-inch diameter limit is to be applied. Each management objective affects the stand value and the cutoff value for a given stand. The objective affects stand value through causing adjustments in the values of trees over the maximum allowable diameter. Also, each objective contains a predetermined cutoff value to be used in stand analysis.

Stand Index Value vs. Cutoff Value

After a stand value is generated for a given objective, it is compared to the predetermined cutoff value for the objective. Any value equal to or above the cutoff value returns a decision to manage the stand and any value below the cutoff value returns a decision to regenerate the stand. Stand values that are near the cutoff value are borderline stands. Therefore, a model decision to manage or regenerate a borderline stand means the stand’s management potential is leaning towards the decision. In borderline

stands, there may be many factors that potentially influence the stand's management potential.

Conversion of Manuel's Bottomland Hardwood Decision-Making Model

Manuel's bottomland hardwood decision-making computer program was created using a Microsoft Disk Operating System (MS-DOS) format in the FORTRAN language. During the time the program was created, MS-DOS computer programs were common and acceptable. However, today with the availability of higher level computer languages such as Visual Basic, Visual C++, Visual C#, and Java, the need to update desirable MS-DOS programs into a Windows environment is important. Manuel's program employs a series of screens filled primarily with list boxes used to retrieve data from the user. Initial stand information including: stand name, plot size, and the mode in which to run the program (2 types: "Demo" and "Cruise"), are retrieved through a series of input screens. The two run modes allow the user to enter stand data in different forms. Demo mode requires the most information about a given stand and produces a more "finely tuned" stand index. Cruise mode requires less information that is usually included in standard inventory cruises. The primary difference between the two modes is that in Demo mode the user must input the tree grade, vigor, crown class, and height, whereas in Cruise mode the user only enters species, species class, diameter, and tree preference class. The end result is that Demo mode provides a more exact result than Cruise mode. Manuel's program retrieves stand data through a spreadsheet screen that contains list boxes for most of the variables.

The new Windows-based program adds a significant amount of functionality to the program. The new program uses spreadsheets containing editable cells and list boxes within dialog boxes to retrieve data from users. The primary element that increases the functionality of the program is the ability to easily edit input variables. This allows the user to quickly see the effects of changing variables, such as the effect on stand value from changing the desirability of certain species.

RESULTS AND DISCUSSION

Because the evaluations of the expert panel are currently being conducted, only preliminary results can be presented at this time. The Cumberland Plateau is providing the highest potential cutoff values in the initial stand analyses. Preliminary stand analyses for the Cumberland Plateau and the Western Highland Rim are presented in figs. 1 and

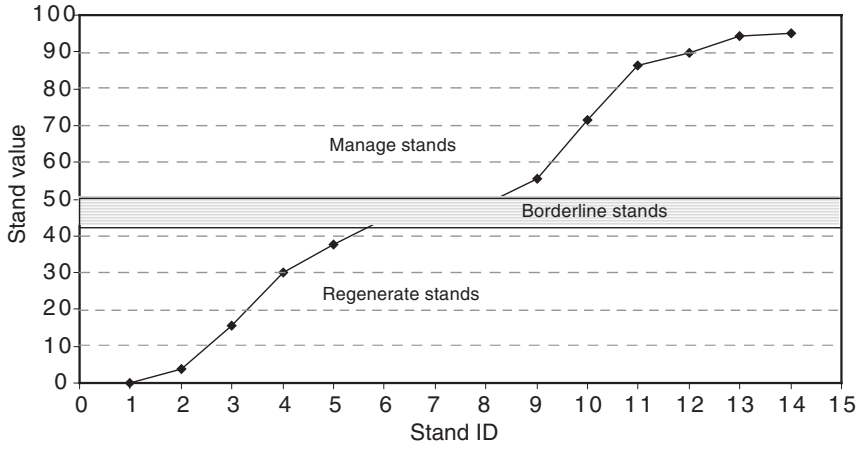

Figure 1— Preliminary stand analysis for the Cumberland Plateau.

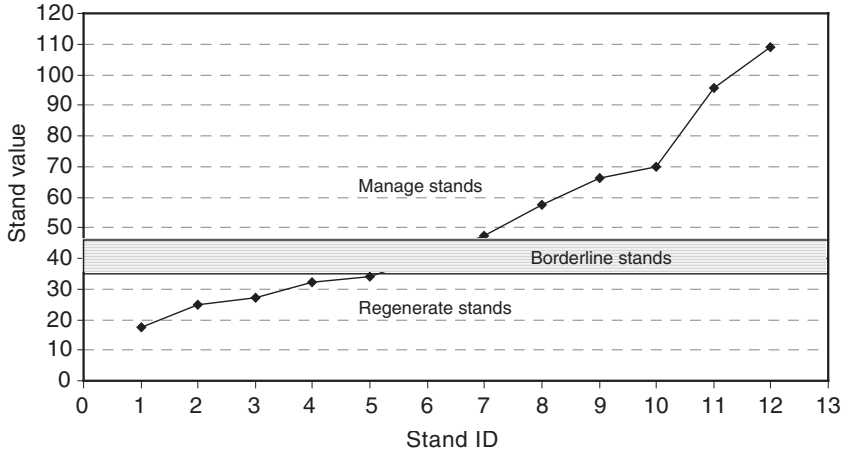

Figure 2—Preliminary stand analysis for the Western Highland Rim.

2. Due to insufficient data at this point, initial stand values for the Upper Coastal Plain are not shown. Initial Stand values for the Cumberland Plateau Province range from 0 to 95. The borderline stands appear to have values that range from 43 to 50. Stands with values below 30 appear to be strong regenerate stands. Stands with values over 70 appear to be highly manageable (as seen in fig. 1). Initial stand values for the Western Highland Rim range from 17 to 109. The borderline stands appear to have values that range from 37 to 47. Stands with values below 30 appear to be strong regenerate stands; stands with values over 60 appear to be highly manageable (fig. 2).

SUMMARY

The product of this study is a decision-making model, which is incorporated in a computer application, for managing or regenerating southern upland hardwoods. The model is an extension of Manuel's (1992) bottomland hardwood decision-making model. The primary variables used in the model include stocking of desirable species, tree preference class, and individual tree characteristics. These variables are used to generate tree values, which are accumulated into plot values and converted to overall stand values. There are four objectives used to represent different management goals in the model. A stand value is compared to the cutoff value for a given objective. Any value greater than or equal to the cutoff value returns a decision to manage a stand. Alternatively, any values less than the cutoff value return a decision to regenerate a stand.

Individually, the expert panel determines each stand to be either manageable or in need of regeneration for a given objective. The decisions of the model are compared to the decisions of the expert panel to gauge the usefulness of the model. At this time, the review by the panel members is being conducted. This model is designed to assist in determining the management potential of upland hardwood stands. Determining whether a stand is manageable or in need of regeneration must be accomplished before any silvicultural prescription is applied. Furthermore, the generation of an upland model, along with the conversion of the bottomland model to Windows, is an attempt to set the stage for completing the modeling of manage/regenerate decisions for southern hardwood stands.

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YELLOW-POPLAR AND OAK SEEDLING DENSITY RESPONSES TO WIND-GENERATED GAPS

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Abstract—The effects of wind on upland hardwood forest structure and composition have been studied mostly in the context of either small "gap-phase" openings or in retrospective studies of ancient disturbances. Larger (> 0.1 ha) wind-created openings are common across Southern Appalachian landscapes, and can be important in shaping understory colonization, growth, and survival. On October 5, 1995, Hurricane Opal struck the Bent Creek Experimental Forest, creating a unique opportunity to investigate the effects of wind damage and wind-created large forest gaps on forest understory vegetation. We investigated the relationships of yellow-poplar (*Liriodendron tulipifera* L.) and oak (*Quercus* spp.) seedling densities to spatial and structural gradients in and around 12 large, Hurricane Opal–created gaps. Seedling densities were modeled with repeated measures regressions over 3 years (1996, 1997, and 1998). Oak seedling density was highest in the south end of gaps and on high-energy aspects. Oak densities were negatively correlated with hurricane-created crown debris cover and large woody debris. Yellow-poplar seedling density was positively related to distance from southern gap edge and predicted soil moisture, and negatively associated with time since disturbance and crown debris. Yellow-poplar density was highest in the light-rich north end of gaps. The oaks were better able to populate the south end of gaps where yellow-poplar competition was less. Forest managers should expect similar natural regeneration trends in manmade gaps, such as group selection openings.

INTRODUCTION

Hurricane-force winds create large gaps (> 0.1 ha) in eastern hardwood forests. These disturbances are important mechanisms for forest understory recruitment and density changes in the Southern Appalachians (Runkle 1985). Because hurricanes create unique understory plant microsites and massive amounts of tree debris in and around wind-created gaps, understory responses vary substantially from those of manmade gaps (Elliott and others 2002).

Understory recruitment and density generally increase as gap size increases, at the photosynthetically active radiation-rich (PAR) north end of gaps, and with reductions in forest canopy (Busing and White 1997, Ehrenfeld 1980). Several investigations have addressed the change in gap understory dynamics relative to categorical gap positions (center, edge, exterior) (Gysel 1951, Palik and Murphy 1990). However, few studies have focused on understory density changes along continuous linear distance gradients from gap exterior towards gap center (Matlack 1994). Knowledge of differential understory species densities along linear distance gradients would enable managers to predict gap partitioning for species of interest.

Hurricane Opal struck the Bent Creek Experimental Forest on October 5, 1995, creating a unique opportunity to investigate the effects of wind damage and resulting large forest gaps on forest understory vegetation. We developed predictive models relating yellow-poplar (*Liriodendron tulipifera* L.) and oak (*Quercus* spp.) seedling densities to spatial and structural gradients in and around the large gaps created by Hurricane Opal.

Our objectives were to test the hypotheses that yellow-poplar and oak seedling densities in and around wind-created gaps increase (1) on a linear distance gradient from outside gap towards gap center, (2) as gap size increases, (3) in the north end of gaps, (4) as tree canopy cover decreases, (5) as wind-created woody debris decreases, (6) as shrub cover decreases, and (7) with time.

METHODS

Sustained winds of 8.9 m/s and maximum peak gusts of 25.9 m/s were recorded at the Asheville, NC, airport during Hurricane Opal. Within a 259-ha surveyed parcel at Bent Creek, an average of 0.89 canopy gaps/ha were created by windfalls from Opal. Single-tree gaps were the most common type of opening, averaging 57±34 m^2. Multiple-tree gaps averaged 171±117 m^2 (Greenberg and McNab 1998).

Gap Selection

The gaps selected for our study were all in the 2400-ha Bent Creek Experimental Forest, located about 16 km south of Asheville, NC (35.5° N., 82.6 ° W.). We restricted our selection to openings at least 0.1 ha in size, with at least six canopy trees per gap downed by Hurricane Opal. Beck (1988) found the 0.1-ha size a reasonable minimum for the successful colonization and development of the most shade-intolerant eastern hardwoods. By selecting gaps > 0.1 ha in size for our study, we ensured that all native hardwoods had enough light to colonize and grow successfully.

Between October 1995 and June 1996 we located 12 gaps meeting the criteria; the selected gaps ranged from 0.13 ha to 1.26 ha in area. We used Runkle's (1992) definition of the extended gap to determine gap perimeters. Hurricane-created windfall trees were mostly uprooted and had not snapped off from their boles.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

All selected gaps supported some residual hardwood overstory and midcanopy trees; residual tree distribution was highly variable. Common overstory species included oaks, hickories (*Carya* spp.), and yellow-poplar. Common midstory species included dogwood (*Cornus florida* L.), sourwood [*Oxydendron arboreum* (L.) DC.], red maple (*Acer rubrum* L.), and blackgum (*Nyssa sylvatica* Marsh.).

Of the 12 gaps, 6 were located in dry oak-hickory vegetation communities, 4 in acidic coves, and 2 in rich coves (Schafale and Weakley 1990). Annual precipitation ranged from 120 cm at 670 m elevation to 150 cm at 850 m elevation. Area soils consisted of gneisses and schists, with occasional intrusions of mafic minerals found in amphibolite deposits. All soils were > 80 cm deep and acidic (pH < 5.2).

Study Design

Sampling points were installed May to July 1996. We located two horizontal perpendicular axes of north-south and east-west within each gap. Axes intersected at gap center. Transect lines extended out from center along the established axes in cardinal directions. We located sampling points at (1) gap center; (2) out from center along transects 7.3 m to 10.67 m apart until gap edge was reached; (3) at the north, south, east, and west gap edges; and (4) progressively outward beyond gap edges 7.3 m apart. The most extreme points were installed outside gaps where ground-level solar radiation approximated that of forests unaffected by windthrow.

This procedure resulted in 15 to 32 sampling points per gap, and 269 points among all 12 gaps. Established sampling points formed the centers of 13-m^2 circular quadrats.

Understory Vegetation Measurements

Yellow-poplar and oak seedlings (propagules of both sprout and seed origin) were censused three times: (1) July to September 1996, (2) September 1997, and (3) July to October 1998. All sprouts and seedlings ≤ 3.81 cm diameter at breast height (d.b.h.) within the 13-m^2 quadrats were censused by species, with only the dominant individual per sprout clump tallied. Because total counts were limited to propagules from seed plus the dominant individual per sprout clump, counted seedling density is in effect a "practical management density," not total density. Oak species counted included northern red (*Q. rubra* L.), chestnut (*Q. prinus* L.), black (*Q. velutina* L.), southern red (*Q. falcata* Michx.), and scarlet (*Q. coccinea* Münchh.).

Variables

We tested a wide array of variables as covariates, including

1. Distance/gap attributes: gap area, gap perimeter, ratios of gap length to width, distance from gap center to edge, distances from north and south gap edges to center, cardinal direction from center, and gap aperture (angle from gap center to canopy tree tops at gap edge (Runkle 1992)
2. Cover: canopy cover of overstory, midstory, and total canopy
3. Solar radiation: direct, indirect, and total PAR received at 1 m aboveground. We used canopy photography to predict PAR
4. Debris and microtopography resulting from Hurricane Opal: crown debris, coarse woody debris, tree-fall pits or mounds
5. Site: slope, aspect, categorical estimates of soil moisture potential (xeric, subxeric, submesic, mesic), elevation, landform index (McNab 1993), and terrain shape index (McNab 1989)
6. Vegetative competition: shrub cover.

(Reference table 1 for the variables used in final vegetation density regression equations.)

Data Analysis

We used repeated measures regression techniques to test all hypotheses. Oak and yellow-poplar seedling densities were regressed against covariates across three time periods: time 1 (1996), time 2 (1997), and time 3 (1998). Data were pooled across all 12 gaps and 269 quadrats.

We used SAS PROC GENMOD (SAS Institute 2000) to model tree seedling densities. Specifically, the REPEATED feature found in GENMOD was used to model density changes with time as generalized estimating equations (Allison 1999). At first we used the Poisson distribution, but we found that variances were substantially higher than means, which violates a critical Poisson distribution assumption. To remedy this overdispersion problem, we modeled seedling densities with the negative binomial distribution. The negative binomial is a generalization of the Poisson and accounts for overdispersion by adding a disturbance term to the regular Poisson model (Allison 1999). The linearized-negative binomial model is:

$$\log \lambda_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_k x_{ik} + \sigma\varepsilon_i$$

where

λ_i = the predicted tree seedling integer count

β s = the intercept and coefficients

x s = the covariates

$\sigma\varepsilon_i$ = the disturbance term.

There are no generally accepted goodness-of-fit measures for generalized estimating equations (GEE). The best overall metric of GEE model performance is a simple ratio of the model's deviance to error degrees of freedom (DF) (Allison 1999). Ideally, deviance to DF should equal 1.0. Using the negative binomial yielded density models with deviance to DF close to this desirable 1.0 ratio. Deviance to DF = 744.211:676 = 1.104 for the all-species model, 1.125 for oak, and 1.104 for yellow-poplar (table 2). Having these ratios close to 1.0 ensured reasonable estimates of parameter standard errors (Allison 1999).

Table 1—Variables used in vegetation density regression models

Variable	Mean	Range	Explanation
	units		
DS	36.1 (m)	-21.00 – 205.00	Distance from south: distance from south gap edge to quadrat. Positive values indicate quadrat is north of south edge; negative values indicate quadrat is south of south edge (Yoshida and others 1998).
YPOSN	1.2 (m)	-112.3 – 109.4	Distance north or south of gap center. Positive values indicate quadrat location north of center; negative values indicate south of center (Yoshida and others 1998).
PRO	3.8 (percent)	0.0 – 75.0	Coarse woody debris suspended aboveground level: ocular estimate of proportion of quadrat surface area covered by woody debris suspended aboveground that resulted from Hurricane Opal; recorded in 1996 on 13 m^2 quadrats.
CROWN	10.7 (percent)	0.0 – 95.0	Crown debris, as above.
YPTOTDEN	3.6 (integer count)	0 – 35	Yellow-poplar seedling density per quadrat; response variable.
OAKDEN	10.5 (integer count)	0 – 57	Oak seedling density per quadrat; response variable.
TRANSASP	0.967 (unitless)	0.0 – 1.996	Transformed aspect: quadrat aspect modified with Beers and others (1966) transformation to give quadrats with aspect of 45° highest values, 225° lowest values.
LFI	0.19 (decimal)	.08 – .34	Landform index (McNab 1993): the degree of protection offered by the surrounding topography, expressed as the percent slope from gap center to the surrounding landscape horizon. The mean of eight readings taken at 45-degree intervals. LFI is an index of predicted soil moisture. Higher values suggest higher soil moisture content.
TIME	N/A	1 – 3	When seedling counts were conducted. Time 1 = 1996, time 2 = 1997, time 3 = 1998.

DS = distance from south gap edge; YPOSN = distance south or north of gap center; PRO = coarse woody debris; CROWN = hurricane-created crown debris cover; YPTOTDEN = yellow-poplar seedling counts; OAKDEN = oak seedling counts; TRANSASP = transformed aspect; LFI = landform index; TIME = when seedling counts were conducted.

RESULTS

We found that seedling densities were strongly related to cardinal direction within gaps. Oak seedling density was highest in the south end of gaps, as indicated by the negative slope of the distance south or north of center (YPOSN) parameter (table 2, fig. 1). Yellow-poplar density was highest in the north end of gaps, as evidenced by the positive distance from south gap edge (DS) parameter (table 2). These two distance gradient covariates are hybrids of cardinal direction and continuous linear distance.

Yellow-poplar densities were positively correlated with gap perimeter, a surrogate for gap size ($r = 0.30$, $P < 0.0001$). However, DS was so highly collinear with gap perimeter ($r = 0.68$, $P < .0001$) that both DS and gap perimeter could not be used in the density model. As the stronger covariate, DS was used in the final yellow-poplar model.

As expected, hurricane-created crown debris (CROWN) significantly reduced predicted seedling densities in both models (table 2, fig. 2). CROWN interacted significantly with time in the oak equation, testifying to the decline of crown debris coverage over the 3-year response period. CROWN also interacted significantly with large woody debris (PRO) in the oak model. This is not surprising. PRO resulted mostly from trees downed by the hurricane, and most downed trees contained live crowns.

Surprisingly, seedling density was not related to canopy cover or predicted solar radiation (table 2). We found no relationship of seedling density to shrub cover. Years 1996, 1997, and 1998 (TIME) was a significant covariate in both models, but time exhibited a meaningful negative trend only in the yellow-poplar model (table 2, figs. 1 and 2).

Physical site variables accounted for significant variation in both density models. Oak densities were highest on high-energy aspects, as evidenced by the negative slope of the transformed aspect (TRANSASP) parameter. Yellow-poplar was positively related to landform index (LFI) and TRANSASP (table 2).

Table 2—Predicted tree seedling counts[a]

Response variable	n	DF	Deviance	Pearson chi-square	Log likelihood	Covariate	Parameter estimate	Empirical standard error	Z value	Prob. > Z
OAKDEN	743	733	824.905	791.856	12,380.976	Intercept	2.8281	0.0782	31.78	< 0.0001
						YPOSN	-0.0057	0.0023	-2.49	0.0129
						TRANSASP	-0.2687	0.0753	-3.57	0.0004
						Time 1 (1996)	-0.2022	0.0326	-6.20	< 0.0001
						Time 2 (1997)	-0.2698	0.0316	-8.54	< 0.0001
						Time 3 (1998)	0.0000	0.0000	.	.
						YPOSN*CROWN	-0.0003	0.0001	-2.24	0.0252
						CROWN*PRO	-0.0012	0.0002	-4.76	< 0.0001
						CROWN*Time 1	-0.0081	0.0027	-3.03	0.0025
						CROWN*Time 2	-0.0044	0.0023	-1.90	0.0581
						CROWN*Time 3	-0.0027	0.0023	-1.19	0.2322
YPTOTDEN	743	737	605.3614	644.175	3,602.978	Intercept	-3.2543	0.3535	-9.21	< 0.0001
						TRANSASP*DS	0.0126	0.0010	12.24	< 0.0001
						CROWN	-0.0111	0.0048	-2.31	0.0211
						LFI	14.7085	1.4249	10.32	< 0.0001
						Time 1 (1996)	0.8707	0.1295	6.72	< 0.0001
						Time 2 (1997)	1.0368	0.1207	8.59	< 0.0001
						Time 3 (1998)	0.0000	0.0000	.	.

DF = degrees of freedom; OAKDEN = oak seedling counts; YPOSN = distance south or north of gap center; TRANSASP = transformed aspect; CROWN = hurricane-created crown debris cover; PRO = large woody debris cover; YPTOTDEN = yellow-poplar seedling counts; DS = distance from south gap edge; LFI = landform index.

[a] All species seedling counts per quadrat measured in 1996, 1997, and 1998. Data are from measurements of 269 quadrats in 1996, 1997, and 1998 taken on 12 Hurricane Opal-created gaps within the Bent Creek Experimental Forest.

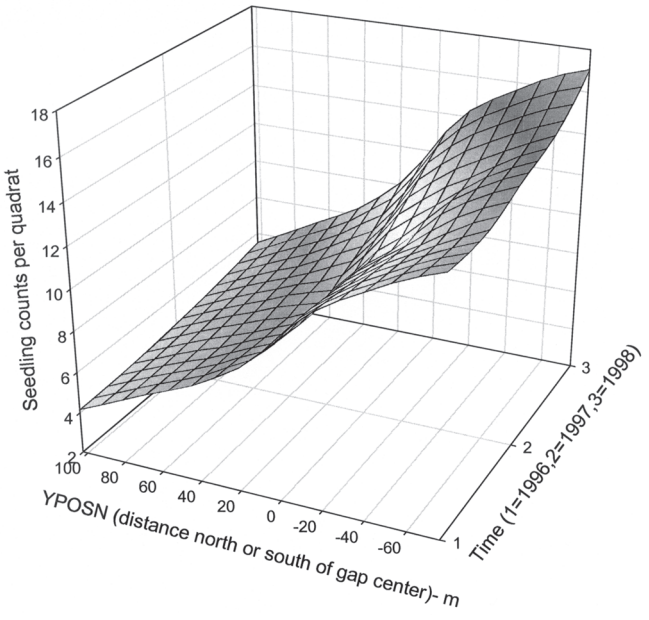

Figure 1—Oak seedling counts per 13-m^2 quadrat vs. YPOSN (distance north or south of gap center; positive values of YPOSN = north of center, negative values = south of center) and time.

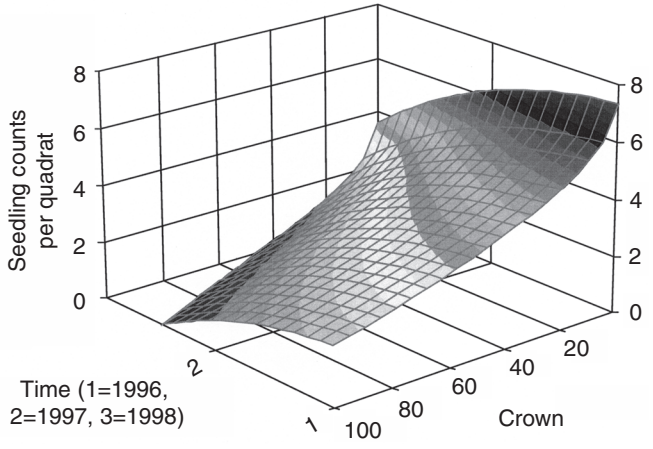

Figure 2—Yellow-poplar seedling counts per 13-m^2 quadrat vs. CROWN (percent crown debris cover) and time.

DISCUSSION

Density models exhibited surprisingly strong relationships over the brief 3-year response period. The significant positive DS covariate (expressed as an interaction term with TRANSASP) in the yellow-poplar seedling model supported the hypothesis that vegetation density would increase in the north end of gaps. However, the opposite was true for

the oak density model, where the negative YPOSN parameter indicated higher oak seedling densities south of gap center (table 2). While both oak and yellow-poplar densities changed on continuous linear distance gradients, regression models for both species groups suggested that maximum densities were not reached at gap center. Final regression models supported our hypotheses that tree seedling densities increased as crown and woody debris decreased. We rejected the hypotheses that seedling densities would increase as gap size increased, as canopy cover decreased, and as shrub cover decreased.

Time showed consistent effects on vegetation density only in the yellow-poplar model, where density marginally decreased over 3 years (fig. 2). Because yellow-poplar seedlings were not tagged at the start of each of the three growing seasons, we can only speculate that the reduction in yellow-poplar seedling density through time is due to germinant mortality. Other investigators' findings of vegetation density change through time on disturbed sites vary widely. Tift and Fajvan (1999) discovered that red maple aggressively invaded small gaps, with substantial numbers of fresh recruits establishing each year for 10 to 15 years longer than other species. Beckage and others (2000) studied hardwood dynamics in the Southern Appalachian region and found that seedling densities remained relatively static for the first 3 years after artificial creation of 0.03-ha gaps. Fresh tree seedling recruits then increased substantially in years 4 and 5. Clinton and Boring's (1994) investigation of tree seedling density and shrub competition showed that although all-species richness declined with time, seedling density increased with time.

The density of shade-intolerant yellow-poplar seedlings increased in the light-rich north end of gaps in this study, concurring with findings of other investigators (Canham 1989, Poulson and Platt 1989). Oak densities followed just the opposite pattern; densities increased towards the south end of gaps. Oaks apparently take advantage of lower yellow-poplar competition in the south end of gaps; they are able to flourish in the reduced PAR environment found south of gap center where yellow-poplar is less successful. Our findings of distinct species and life-form density differences among gap locations support the gap-partitioning theory (Bazzaz 1996).

We did not find increases in oak and yellow-poplar seedling densities with increasing gap size, although most other investigators have found strong positive relationships between seedling density and gap size (Busing and White 1997, Collins and Pickett 1987). In particular, shade-intolerant species require larger gaps. Busing and White (1997) found that shade-intolerant arborescent recruitment depended on gaps > 0.04 ha. Beckage and others (2000) discovered that only red maple would successfully colonize 0.03 ha or smaller gaps. We suspect that selecting gaps > 0.1 ha diluted the effect of gap size on understory vegetation response in our study.

Increased understory density is often strongly correlated with increases in beneath-canopy PAR (Carvell and Tryon 1961, Crow and others 2002). For this study, however, oak and yellow-poplar seedling densities were not strongly related to PAR. There are several probable reasons for this. Arborescent seedling densities were mostly negatively correlated with PAR indices. These correlations were weak (r = -0.10 to -0.15 with P = 0.02 to 0.05) due to high variability in height, but indicated that dense vegetation was often taller than the 1-m measurement height and, therefore, covered the camera lens used to measure PAR. Hemispherical photos were taken in 1998, at the end of the response period. If the photos had been taken in 1996, the 1-m instrument height would probably have been above most tree seedlings, and predicted radiation may have been closely related to seedling density.

Unlike Peterson and others (1990), we found no relationship between vegetation density and pit or mound topography. We suggest that because only a small fraction of gap areas were covered with pits and mounds, few tree seedlings were located on these microsites, making any statistical relationships improbable.

Physical site variables facilitated a pooled-data approach for all 12 gaps. Oak densities were higher on high-energy aspects, as evidenced by the significant positive TRANSASP covariate in the oak model. We suggest that this is a competition-related phenomenon. In our experiment, yellow-poplar thrived on low-energy aspects and mesic sites and probably inhibited oak colonization. Oaks are able to capitalize on the lack of arborescent seedling competition found on more xeric sites and recruit successfully (Johnson and others 2002). These findings of higher oak densities on drier sites conform to those of Jenkins and Parker (2000) and Carvell and Tryon (1961).

Seedling densities exhibited surprisingly poor relationships to overstory and midstory canopy cover in our study. Other researchers have mostly found increases in vegetation density with reductions in canopy cover (Buckley and others 1997, Clark and others 1999, Jenkins and Parker 2000). In a previous investigation, seedling survivorship and growth were negatively correlated with canopy cover (Berg 2002).

Unlike other investigators, we found no relationship between tree seedling density and shrub cover (McKenzie and others 2000, Wetzel and Burgess 2001). We had expected substantial reductions in understory density with increasing shrub cover. This lack of relationship is probably due to the light overall shrub cover on our sites. Mean shrub cover among all 269 quadrats increased from just 9.3 percent in 1996 to 14.2 percent in 1998. There were few quadrats where shrub cover exceeded 30 percent. Further, few quadrats contained rhododendron (*Rhododendron maximum* L.), a species shown to substantially dampen tree seedling colonization (Baker and Van Lear 1998, Beckage and others 2000, Clinton and Boring 1994). Some quadrats on drier sites were covered with mountain laurel (*Kalmia latifolia* L.). As did Waterman and others (1995), we found that mountain laurel did not suppress tree seedling density.

Tree seedling densities were substantially diminished by hurricane-created crown debris (table 2). We suggest that crown debris probably eliminated growing space opportunities for new understory recruits and killed advance regeneration by crushing or smothering.

CONCLUSIONS

1. Yellow-poplar seedling densities increased in the north end of gaps; oak densities and herb species richness were greater in the south end of gaps; these findings support the gap-partitioning theory
2. Hurricane-created crown debris significantly retarded tree seedling density
3. Oak and yellow-poplar seedling densities were not related to canopy cover or shrub cover
4. Oak and yellow-poplar seedling densities were not related to gap size. Yellow-poplar density was positively related to gap perimeter length, but this relationship was eclipsed by a stronger, collinear covariate for distance from southern gap edge
5. Yellow-poplar seedling density decreased over the 3-year response period. Oak seedling density remained essentially unchanged through time
6. Physical site variables proved useful in explaining differences in tree seedling density.

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Hardwood Intermediate Treatments

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INTERMEDIATE CUTTING IN MIXED UPLAND OAK STANDS ON THE WESTERN HIGHLAND RIM, TENNESSEE, AFTER A QUARTER OF A CENTURY

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Abstract—In 1973 and 1974, a study was established at Stewart State Forest (SSF) and Lewis State Forest (LSF) to evaluate Roach and Gingrich's "Even-Aged Silviculture for Upland Central Oaks" on the Western Highland Rim. Harvesting to the "B-level" of the stocking guide primarily removed cull and low-quality stems. Basal area was reduced from 110 to 80 square feet per acre at SSF and from 99 to 75 square feet per acre at LSF. Although there were no differences between uncut and cut plots before harvest at either state forest, density, basal area, volume and value were significantly higher on the uncut plots immediately after harvest and also at 10 and 26/27 years, except for number of merchantable trees at age 26/27. Current value of the sawtimber and of all merchantable trees was not significantly different between uncut and cut plots. After a quarter of a century, the number of saplings decreased substantially on both the cut and uncut plots at both state forests. At SSF, at least 90 percent of the saplings were undesirable timber species or understory species; at LSF, nearly 70 percent were undesirable.

INTRODUCTION

The Western Highland Rim (WHR) in Tennessee encompasses nearly 4.5 million acres in all or parts of 20 counties. More than half of it is forested. Adoption of sound silvicultural practices progressed slowly in this area, and past abuses, such as heavy, repeated cuttings for charcoal production and logging to small diameters for crossties and lumber, made the trees in many stands poor indicators of site quality and potential productivity (Clatterbuck 1991). Although some sites are too poor for profitable timber production, there is substantial area where productivity could be improved with good silvicultural practices, including intermediate stand treatments.

Silvicultural guides for upland central hardwoods developed by researchers at the U.S. Department of Agriculture, Forest Service's Northeastern, North Central, and the former Central States Forest Experiment Stations were thought to be generally applicable to the mixed oak forests of the WHR. Roach and Gingrich (1968) summarized information on hardwood silviculture in Agriculture Handbook 355, "Even-Aged Silviculture for Upland Central Hardwoods". It synthesized even-aged silvicultural prescriptions for a broad array of stand structures, densities, and species mixtures for three site classes based on black oak (*Quercus velutina*) site index with the objective to "..grow full yields of the highest value products the site can produce in a relatively short time." This objective was compatible with the need for improvement in WHR forests for maximum volume and quality lumber production.

This study was established in 1973 and 1974 to test the local applicability of Roach and Gingrich's guide to silviculture for upland central hardwoods. Specific objectives of this study were to determine the effects of intermediate treatments on number of stems, stand basal area, volume, and quality of growing stock by species group.

STUDY SITES

Warm, humid summers and mild winters characterize the climate on the WHR. The average temperature ranges from about 40 °F in the winter to about 80 °F in the summer. The mean annual precipitation is about 45 inches. The wettest months of the year are January through March (Smalley 1980).

Site and stand criteria included: (1) topography typical of the WHR [slopes of 30 to 60 percent and relief of 200 to 600 feet]; (2) upland oak stands [oak (*Quercus* spp.) comprising at least 50 percent of the basal area] that were fully stocked; (3) medium to good sites [site index at least 55 feet for black oak].

As originally conceived, this study was to be established at six to eight locations. However, only two were established because of budgetary constraints. The two locations are Lewis State Forest (LSF), near Hohenwald, TN, and Stewart State Forest (SSF), near Erin, TN.

Both study areas are located on cherty, gently sloping to steep, north slopes classified as Landtype 5 according to Smalley's (1980) land classification system for the WHR. Landtype 5 has moderately deep to deep cherty silty and clayey soils that are well drained to somewhat excessively drained with a relatively high soil-water supply, and that are strongly acid with moderate to moderately low fertility. Estimated site indices (base age 50) for natural stands are 70 for upland oaks, 90 for yellow-poplar (*Liriodendron tulipifera*), and 75 for loblolly pine (*Pinus taeda*).

Stewart State Forest

Plots on SSF range from 400 to 500 feet in elevation. The age of the overstory, at establishment, averaged 71 years with a few trees over 100 years old. Seventy-five percent of sawtimber trees were white oak (*Q. alba*), northern red oak (*Q. rubra*), and black oak. Ten percent were yellow-poplar,

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

and 10 percent were hickories (*Carya* spp.). Minor sawtimber species included sugar maple (*Acer saccharum*), scarlet oak (*Q. coccinea*), and chinkapin oak (*Q. muehlenbergii*). About 75 percent of sawtimber trees were classified as acceptable, and 25 percent were unacceptable growing stock, as defined by Roach and Gingrich (1968).

Forty-five percent of the pole-sized trees were hickories, 29 percent were white and northern red oaks, and 6 percent were blackgum (*Nyssa sylvatica*). Minor species included white ash (*Fraxinus americana*), sugar maple, yellow-poplar, black cherry (*Prunus serotina*), black oak, scarlet oak, sourwood (*Oxydendrum arboreum*), flowering dogwood (*Cornus florida*), cucumbertree (*Magnolia acuminata*), American hornbeam (*Carpinus caroliniana*), eastern hophornbeam (*Ostrya virginiana*), and American elm (*Ulmus americana*). About 27 percent of poles were acceptable, 53 percent were unacceptable, and 20 percent were culls.

Of the sapling-sized trees, only about 10 percent were of desirable sawtimber species: hickories, white ash, white oak, yellow-poplar, and black cherry. Other timber or understory species present included eastern hophornbeam, flowering dogwood, blackgum, eastern redbud (*Cercis canadensis*), sassafras (*Sassafras albidum*), American hornbeam, sourwood, and American beech (*Fagus grandifolia*).

Lewis State Forest

Plots on LSF range in elevation from 860 to 920 feet. The age of the overstory, at establishment, averaged 59 years but ranged from 44 to 80 years with a few trees over 100 years. Of the sawtimber trees, 52 percent were scarlet and white oak, 24 percent were southern red oak and black oak, and 8 percent were yellow-poplar. Minor species included northern red oak, post oak (*Q. stellata*), hickories, and blackgum. About 62 percent of sawtimber-sized trees were rated as acceptable, 12 percent as unacceptable, and 26 percent as culls.

Forty-four percent of the pole-sized trees were white oak, 10 percent were scarlet oak, and 8 percent were black oak. Minor species included hickories, yellow-poplar, northern red oak, southern red oak (*Q. falcata*), chestnut oak (*Q. prinus*), post oak, blackgum, sourwood, flowering dogwood, sweetgum (*Liquidambar styraciflua*), and sassafras. About 76 percent of poles were rated as acceptable, 15 percent as unacceptable, and 9 percent as culls.

Eighty-five percent of the sapling-sized trees were white oak, hickories, flowering dogwood, and blackgum. Minor species included sugar maple, sassafras, northern red oak, post oak , chestnut oak, and yellow-poplar.

METHODS

Four plots, ranging in size from 0.87 to 1.26 acres, were established at each state forest. Two plots were randomly selected for treatment in 1974 and 1975, whereas two plots served as controls.

The basis for determining the cut was Roach and Gingrich's (1968) stocking guide. The basal area removed was equal to the difference between the basal area of the initial inventory and the "B-Level" of the stocking guide, which is the minimum density required for full site utilization, or about 58 percent of full stocking. Two to three square feet of basal area were reserved for expected loss of trees due to damage from logging.

All culls and some unacceptable growing stock trees [diameter at breast height (d.b.h.) > 4.5 inches] were removed in the cut and, at SSF, a few relics were also removed. Merchantable trees were felled, skidded off the plot, and utilized whereas unmerchantable trees were injected with an herbicide. A light fire burned at SSF after the initial inventory but before the first growing season after treatment; damage was confined to understory plants.

Stand inventories were conducted in each plot prior to treatment. The initial inventory consisted of 100-percent tally of growing stock trees. Data collected included d.b.h., species, and rating of trees as acceptable, unacceptable, or cull growing stock according to Roach and Gingrich's guide. Each tree was assigned a consecutive number and tagged with that number for use throughout the study. Ingrowth trees were determined at each subsequent inventory, tallied, tagged, assigned a continuing consecutive number for that plot, and their species and d.b.h. determined. On the cut plots, numbers of cut trees were noted to allow calculation of "after cut" values. D.b.h. of live trees was measured 3, 5, 10, and 26 or 27 years after the cut.

A note concerning the periods after harvest: LSF was cut in 1974 and SSF was cut in 1975. We measured both state forests in 2002; thus, LSF was measured 27 years after harvest and SSF was measured 26 years after harvest. This one-year difference after a quarter of a century should have little impact on the results.

Originally, 6 to 21 trees were selected per plot for detailed measurement and use in estimating volume. In the most recent measurement, bark thickness at breast height, diameter outside bark (d.o.b.) at the top of the first log, and height to a 4-inch d.o.b. or height to the end of merchantable material and d.o.b. at that point, were measured. These data were used to develop local volume equations that were then used to estimate volume of all trees in the study for all inventories.

Sawtimber and total values were based on delivered prices for West Tennessee in the 4th Quarter 2001 Tennessee Forest Products Market Report (Tennessee Department of Agriculture, Forestry Division 2001). Hardwood pulpwood was quoted at $56.26 per cord, mixed hardwood sawtimber at $127 per thousand board feet (MBF) (Doyle log rule), and oak sawtimber at $357 per MBF (Doyle log rule). Doyle prices were converted to International ¼ inch by multiplying the price by 0.61. The conversion factor for pulpwood was 85 cubic feet per cord.

Twelve or 15 1/100-acre sample plots were systematically located in each plot. At each measurement, saplings (1.0 to 4.5 inches in d.b.h.) were measured to a 10th of an inch.

Stand characteristics available were density (trees per acre, trees > 0.9 inches in d.b.h.), basal area (square feet

per acre, trees > 0.9 inches in d.b.h.), stand volume (cubic feet per acre to 4-inch d.o.b., trees > 4.5 inches in d.b.h.), and sawtimber volume [board feet (International ¼ inch) per acre to 8-inch d.o.b., trees > 11.5 inches in d.b.h.).

Statistical analyses were conducted using SAS Version 7.0 at an error level of alpha = 0.05 to indicate significant differences. Analysis of variance (PROC GLM) was used to detect treatment differences between state forests and between treatments for each variable. Significant differences among means were detected using F-tests; comparison of means was made using Duncan's Multiple-Range Test.

RESULTS

First, the conditions at each measurement at SSF will be compared with those at LSS, and then the cut plots will be compared to the uncut plots. No comparison of cut plots and uncut plots at individual state forests will be made because treatment/location interactions were not significant.

SSF had significantly fewer trees than LSF throughout the study (table 1). SSF had significantly more basal area until the last measurement when there was no difference. This same trend was also found for stand volume. For sawtimber volume, SSF had more than LSF over the entire period since treatment.

Before harvest, the uncut plots were not significantly different from the cut plots (table 2). After harvest, the cut plots had significantly less timber than the uncut plots, except at the last measurement, when trees per acre, stand value, and sawtimber value were no longer different between cut

Table 1—Stand characteristics for Stewart State Forest and Lewis State Forest on the Western Highland Rim, TN, averaged over cut and uncut plots, before, immediately after, and 10 and 26/27 years after an intermediate cut

Stand characteristic	Location	Time of measurement			
		Pre-cut	Post-cut	10 years	26/27 years
Trees[a] (*per acre*)	SSF	154*[b]	129*	122*	116*
	LSF	199*	177*	167*	146*
Basal area[a] (*ft² per acre*)	SSF	98*	83*	97*	111
	LSF	78*	67*	84*	107
Volume[a] (*ft³ per acre*)	SSF	4,942*	4,187*	4,875*	5,624
	LSF	3,900*	3,340*	4,185*	5,406
ST volume[c]	SSF	11,703*	9,612*	13,475*	17,628*
	LSF	4,342*	3,423*	6,491*	12,781*

SSF = Stewart State Forest; LSF = Lewis State Forest.

[a] For merchantable trees (d.b.h. > 4.5 inches).

[b] A * indicates significant difference between state forests for time of measurement at α = 0.05.

[c] Sawtimber volume in board feet (International ¼ inch) per acre, trees >11.5 inches d.b.h.

Table 2—Stand characteristics for cut and uncut plots averaged over Stewart State Forest and Lewis State Forest on the Western Highland Rim, TN, before, immediately after, and 10 and 26/27 years after an intermediate cut

Stand characteristic	Treatment	Time of measurement			
		Pre-cut	Post-cut	10 years	26/27 years
Trees[a] (*per acre*)	Uncut	174	174*[b]	158*	135
	Cut	179	133*	130*	127
Basal area[a] (*ft² per acre*)	Uncut	88	88*	100*	114*
	Cut	89	63*	80*	104*
Volume[a] (*ft³ per acre*)	Uncut	4,376	4,376*	5,042*	5,766*
	Cut	4,466	3,151*	4,017*	5,264*
ST volume[c] (*bd ft per acre*)	Uncut	8,184	8,184*	11,700*	16,105*
	Cut	7,861	4,851*	8,266*	14,304*
Value[d] (*$*)	Uncut	1,989	1,989*	2,669*	3,424
	Cut	1,927	1,234*	1,895*	3,063
ST value[e] (*$*)	Uncut	1,517	1,517*	2,171*	2909
	Cut	1,432	870*	1,478*	2,585

[a] For merchantable trees (d.b.h. > 4.5 inches).

[b] A * indicates significant difference between treatments for time of measurement at α = 0.05.

[c] Sawtimber volume in board feet (International ¼ inch) per acre.

[d] Value per acre for sawtimber and pulpwood.

[e] ST value is value per acre for sawtimber only.

and uncut plots. Of note is the more rapid increase in stand characteristics for the cut plots as compared to the uncut plots.

Results by growth component provide insight into where the growth occurred. For stand volume, mortality on the uncut plots exceeded that on the cut plots (table 3). For the first decade, it was about a third more, whereas for the 10-year to 26/27-year period, it was about twice that on the cut plots. Ingrowth on the uncut plots was slightly less than that on the cut plots for both periods. Similarly, growth of the surviving trees was slightly less on the uncut plots than on the cut plots.

For the sawtimber trees, mortality on the uncut plots was similar to that on the cut plots during the first decade (table 4). From 10 years to 26/27 years after treatment, mortality on the uncut plots was about three times that on the cut plots. Ingrowth on the cut plots was about 30 percent more than on the uncut plots during the first decade and about 40 percent more from 10 years to 26/27 years. Growth on the surviving trees in the cut plots was only about 75 percent of that on the uncut plots during the first decade and about 90 percent from 10 years to 26/27 years. The slower growth on survivors on the cut plots was surprising.

Trees per acre and stand basal area for both uncut and cut plots were plotted on the stocking chart (fig. 1). Here initial, 10-year, and 26/27-year values are shown. Two trends are evident. First, the cut plots had very little mortality relative to the uncut plots. Second, the cut plots have not attained the stocking of the uncut plots, but the cut plots should soon match the uncut plots, given their current growth rate.

Comparing species of merchantable trees initially with species 26/27 years after treatment, there was little change in the proportion of basal area for each species. At SSF

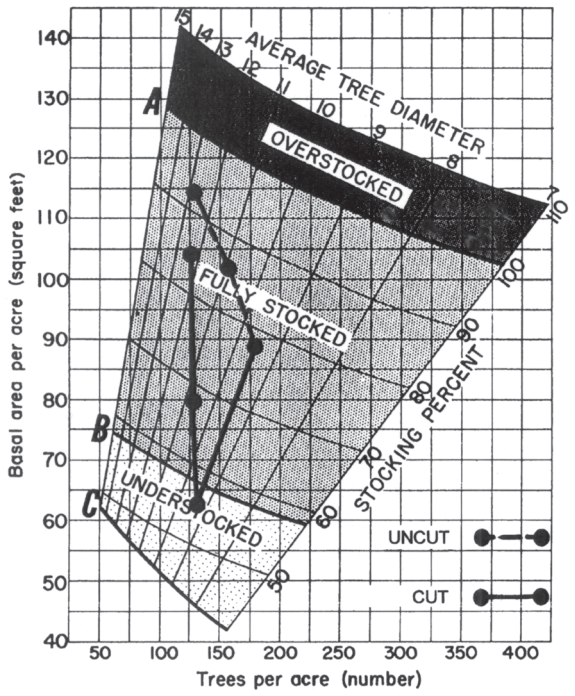

Figure 1—Graph of uncut and cut plot means on stocking chart (Roach and Gingrich 1968) before cut and immediately after, 10 years after, and 26/27 years after an intermediate cut in mixed oaks averaged over Stewart State Forest and Lewis State Forest, Western Highland Rim, TN.

uncut plots, white oak had the most basal area, followed by hickory, northern red oak, and black oak (table 5). On the cut plots, northern red oak was followed by white oak, hickory, black oak and yellow-poplar. Most of the major species increased in basal area. Mostly white oak, northern red oak, hickory, and black oak were harvested. White oak,

Table 3—Stand volume (cubic feet per acre, merchantable trees, d.b.h. > 4.5 inches) growth components for cut and uncut plots averaged over Stewart State Forest and Lewis State Forest on the Western Highland Rim, TN, for two periods after an intermediate cut

		Cut to 10 years			10 years to 26/27 years			
Treatment	Post-cut volume	Mort.	Ingrowth	Survivor growth	Mort.	Ingrowth	Survivor growth	Final volume
Uncut	4,376	485	78	1,057	853	71	1,522	5,766
Cut	3,180	357	90	1,105	420	99	1,567	5,264

Table 4—Sawtimber volume [board feet (International ¼ inch per acre), d.b.h. > 11.5 inches] and growth components for cut and uncut plots averaged over Stewart State Forest and Lewis State Forest on the Western Highland Rim, TN, for two periods after an intermediate cut

		Cut to 10 years			10 years to 26/27 years			
Treatment	Post-cut volume	Mort.	Ingrowth	Survivor growth	Mort.	Ingrowth	Survivor growth	Final volume
Uncut	8,184	567	1,316	2,709	1,880	1,813	4,532	16,105
Cut	4,907	511	1,744	2,125	625	2,617	4,007	14,305

Table 5—Stand basal area (square feet per acre) for merchantable trees (d.b.h. > 4.5 inches) by species or species group for cut and uncut plots at Stewart State Forest and Lewis State Forest on the Western Highland Rim, TN, before and 26/27 years after an intermediate cut

Location	Time of measurement	Treatment	Species or species groups					
			White oak	Northern red oak	Black oak	Yellow-poplar	Hickories	Other species
SSF	Initial	Uncut	30.12	16.65	14.80	7.46	21.11	7.79
		Cut	19.57	26.25	15.08	12.73	16.07	7.56
	26 years	Uncut	39.52	20.18	10.12	14.19	24.22	8.47
		Cut	29.17	26.92	6.71	19.52	17.40	6.13
Location	Time of measurement	Treatment	White oak	Southern red oak	Black oak	Scarlet oak	Yellow-poplar	Other species
LSF	Initial	Uncut	26.61	5.37	6.40	9.17	5.60	11.15
		Cut	29.72	6.86	9.17	13.68	5.18	15.20
	27 years	Uncut	44.05	7.78	6.87	25.48	16.00	14.60
		Cut	47.49	6.45	6.90	15.44	14.60	9.91

SSF = Stewart State Forest; LSF = Lewis State Forest.

northern red oak, yellow-poplar, and hickory increased in basal area during the subsequent quarter of a century. However, black oak decreased in basal area on both the uncut and cut plots.

At LSF, there was little change in the proportion of basal area by species (table 5). White oak had the most basal area, and scarlet oak, yellow-poplar, southern red oak, and black oak were additional major components. Here, the harvest was concentrated in white oak, red oaks, and hickory. All species added basal area whether on the cut plots or on the uncut plots. White oak grew faster on the cut plots.

Saplings were grouped into desirable sawtimber species, other sawtimber, and understory woody species. No differences were found in number of stems per acre either before the cut or at 26/27 years. As with merchantable trees, differences were found between state forests. At LSF, there were considerably fewer seedlings of desirable sawtimber species and understory species, whereas other sawtimber species were about the same (table 6). The only species or species group that increased in number was sweetgum. At SSF, saplings in all categories decreased in number. The only species in large number at age 26 years was sugar maple, which accounted for about three-quarters of the total of other sawtimber species.

IMPORTANT FINDINGS

1. Although uncut plots and cut plots initially had the same cubic-foot volume, the cut plots still contained about 500 cubic feet per acre less than the uncut plots.

Table 6—Number of saplings (stems 1.0 to 4.5 inches d.b.h.) per acre by species or species group for cut and uncut plots at Stewart State Forest and Lewis State Forest on the Western Highland Rim, TN, before and 26/27 years after an intermediate cut

Location	Time of measurement	Treatment	Species or species groups						
			White oak	Red oak group	Yellow popar	Hickory	Sweetgum	Other ST species	Understory species
SSF	Initial	Uncut	8.3	0	4.2	25.0	0	291.7	379.2
		Cut	8.3	0	4.2	4.2	0	283.3	404.2
	26 years	Uncut	0	0	8.3	8.3	50.0	212.5	141.7
		Cut	0	0	58.3	0	12.5	175.0	170.8
LSF	Initial	Uncut	211.6	38.3	6.7	163.4	0	85.9	217.5
		Cut	183.4	16.7	0	163.4	0	80.0	193.4
	27 years	Uncut	38.3	0	13.3	15.0	99.2	21.7	140.0
		Cut	26.7	0	20.0	46.7	76.7	6.7	100.0

ST = sawtimber; SSF = Stewart State Forest; LSF = Lewis State Forest.

Board-foot volumes on cut plots had about 1800 board feet per acre less volume than uncut plots.

2. Both stands added cubic-foot and board-foot volume at rapid rates, but more of the growth was added to acceptable quality trees on cut plots than on uncut plots.
3. The intermediate cut increased the percentage of acceptable sawtimber and poles, particularly in the oaks, by removing the culls and some of the unacceptable trees.
4. Mortality, mostly oaks, greatly affected the growth of the uncut plots and cut plots at both state forests. More cubic-foot volume and board-foot volume were lost to mortality and less gained from ingrowth on uncut plots than on cut plots. Survivor growth was less on uncut plots than on cut plots for cubic-foot volume, whereas uncut plots had more board foot survivor growth than cut plots.
5. There was little net ingrowth of saplings to poles because the cuts were implemented at either state forest.
6. The number of saplings was substantially less on both the cut and uncut plots at both state forests after a quarter of a century. At SSF, 90 percent or more of the saplings were undesirable timber species or understory species; at LSF, nearly 70 percent were undesirable. Many of the undesirable saplings should now be deadened.
8. The intermediate cut at both state forests failed to promote advance reproduction of oaks. Evidently, the openings were not sufficiently large to produce the microenvironment necessary for oak regeneration.
9. Despite the complicating effects of oak mortality, the data show that middle-aged mixed oak stands on cherty north slopes do respond to stand density control, and that the proportion of acceptable quality trees can be substantially increased by an intermediate cut using Roach and Gingrich's basal area guide.
10. Although the cut plots have not yet achieved the basal area or volume of the uncut plots, Roach and Gingrich's recommendations for intermediate stand management remain sound silvicultural advice for WHR mixed oak stands, i.e., remove culls and unacceptable growing stock and concentrate growth on acceptable growing stock. Whether this removal can be an economical operation will depend on markets and volume and value of trees marked for removal.

ACKNOWLEDGMENTS

This study was established and originally maintained by personnel at the Silviculture Laboratory, formerly maintained at Sewanee, TN, by the USDA Forest Service, Southern Forest Experiment Station, in cooperation with the University of the South. Personnel from the Tennessee Division of Forestry assisted in the establishment and measurement of the study. We express our thanks to personnel of both organizations for their work on this study.

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DIAMETER-GROWTH AND EPICORMIC BRANCHING RESPONSE OF AN EAST TEXAS BOTTOMLAND RED OAK STAND 3 YEARS AFTER THINNING AND FERTILIZATION

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Abstract—To determine the effects of intermediate silvicultural treatments on bottomland hardwoods, two types of thinning (crown thinning and low thinning) and one level of fertilizer (200 pounds per acre N + 50 pounds per acre P) were applied to a predominantly red oak stand in southeastern Texas. Treatments were applied in a 3 by 2 factorial arrangement as a randomized complete block design of 12 acres in size. Crop trees were selected prior to the treatments, and diameter at breast height measurements were taken pretreatment and for 3 proceeding years to assess diameter-growth response of all trees. Epicormic branching measurements were also taken for 3 years posttreatment to evaluate epicormic branching response of all crop trees to crown thinning, low thinning and fertilization. First-year results showed no significant difference in current annual increment (CAI) of crop-tree diameter-growth response; however, second-year results of CAI diameter growth showed that crop trees in thinned plots achieved significantly more growth than in unthinned plots. With third-year results of CAI diameter growth, crop trees in crown-thinned plots grew significantly better than in both low-thinned and unthinned plots, all regardless of fertilization. Epicormic branching was generally greater in crown-thinned and fertilized plots immediately following treatment.

INTRODUCTION

Bottomland hardwood forests occur mainly on floodplain sites of recent alluvium; however, other nonalluvial wet sites can support many of the same hardwood species (Hodges 1994). Alluvial floodplains themselves occur along most streams within the United States, but they are most common and most extensive in the Atlantic Coastal Plain, east Gulf Coastal Plain, Mississippi River Alluvial Plain, and west Gulf Coastal Plain (Hodges 1997). Approximately 30 million acres of bottomland hardwood forests remained in the Southeastern United States in 1994, which is less than one-half of such acreage present at the time of European settlement (Hodges 1994). Much of this acreage reduction was a result of conversion to agricultural use within the Mississippi River Alluvial Plain. Currently there are 214 million acres of forested land in the Southeast (Wear and Greis 2002). Of that, more than 32 million acres are considered forested wetlands including bottomland hardwood forests. Furthermore, according to Hodges and Switzer (1979), most bottomland areas are potentially very productive; however, they are growing below their potential due to the past practices of high grading and lack of effective management. This statement could be made about current hardwood forests as well (Allen and others 2001, Devall and others 2001, Stanturf and others 2001).

One of the cornerstones of silviculture is thinning, which can be defined as any cutting made in an immature stand to stimulate the growth of residual trees as well as to redistribute stand growth by utilizing potential mortality (Hawley and Smith 1954). This research project is concerned with two types of thinning: crown thinning and low thinning. Crown thinning (also known as high thinning or thinning from above) involves removing trees from upper crown classes to favor development of the best trees of the same crown classes (Smith and others 1997). Low thinning (also known as German thinning or thinning from below) is aimed at anticipating mortality and salvaging yield (Daniel and others 1979). This method involves removing trees from the lower crown classes to speed up the natural process of self-thinning (Smith and others 1997).

Fertilization can often be a difficult tool to understand in forest management and is rarely used in hardwood silviculture. Sometimes fertilization will favor strong trees so that it will hasten suppression of weaker trees (Smith and others 1997). There may even be cases, with soils extremely deficient in nutrients, where fertilization must be coupled with thinning to produce any effect. The following concentrations of nitrogen (N), phosphorous (P), and potassium (K) are considered adequate in most higher plants (gymnosperms and angiosperms): 15,000 mg per kg (N), 2,000 mg per kg (P), and 10,000 mg per kg (K) in dry plant tissue (Salisbury and Ross 1992). However, Stone (1977) found growth in young even-aged stands is more limited by competition between trees than by availability of N, P, or K, on well-drained soils with site indices of 60 or better.

In a publication intended to inform private landowners about bottomland forest management, the Louisiana Department of Agriculture and Forestry (LDAF; 1995) advocated low thinning to "leave the largest, most desirable trees to provide seeds . . . [and] eventually raise the quality of the whole forest." They may leave crown thinning out of their prescription because of the general landowner's temptation to high-grade during a crown thinning. In keeping with LDAF (1995), Allen and others (2001) also proposed low thinning as the best intermediate bottomland hardwood thinning treatment. They supported this statement by saying healthy trees generally require a live crown to total height

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

ratio of 40 percent or greater, and trees below this proportion are most likely in subordinate crown positions. In a similar publication intended for general hardwood management in Canada, Robertson and others (1991) advocated crown thinning but specifically warned against highgrading of timber stands; they did not discuss low thinning as an option. It is clear there are differing philosophies related to thinning in general as well as thinning in hardwood forests. Therefore, the objectives of the present study are to determine the effects of crown thinning, low thinning, and fertilization on crop tree diameter growth and epicormic branching in an east Texas bottomland red oak stand.

MATERIALS AND METHODS

Study Site

The bottomland red oak stand in this study is located in Angelina County, TX. It is situated in eastern Texas in the western gulf section of coastal plains and flatwoods within the Outer Costal Plain Mixed Forest Province (Keys and others 1995). The major forest type of this area is southern pine with mixed hardwoods. The study area is located on both sides of the Shawnee Creek floodplain, which drains into the Neches River. Shawnee Creek can be described as a minor bottom according to the definition of Hodges and Switzer (1979). The closest incorporated town to the study area is Zavalla, TX. The land is currently owned by Temple-Inland Corporation of Diboll, TX, and is leased to Wolf Creek Hunting Club of Zavalla, TX.

Soils found on the study site are of the Pophers Series, which are classified as fine-silty, siliceous, acid, thermic Aeric Fluvaquents (Dolezel 1988). These soils are somewhat poorly drained and slowly permeable. Due to a slope of less than 1 percent, runoff is slow. This soil overflows two to three times per year in most years, and flooding lasts for several days. The water table is at or near the surface during the cool season, and due to frequent flooding and extended wetness, pine seedlings should not be planted on this type of soil. Pophers soil is used almost entirely as woodland and is well suited for production of quality hardwoods such as water oak (*Quercus nigra* L.), willow oak (*Quercus phellos* L.), and swamp chestnut oak (*Quercus michauxii* Nutt.) (Dolezel 1988). This was proven by estimating site index (base age 50 years) to be 90 to 95 for cherrybark oak (*Quercus pagoda* Raf.), water oak, and willow oak, using the method suggested by Baker and Broadfoot (1979).

History, Climate, and Forest Cover Type

The site was originally intended for regeneration of a loblolly pine (*Pinus taeda* L.) plantation (Personal Communication. Matthew Lowe, Research Forester, Temple-Inland Forest Products Corporation, P.O. Drawer N, Diboll, Texas 75941). It was mechanically prepared by shearing, and herbicides were not used. However, soon after the seedlings were planted, circa 1970, flooding resulted in high seedling mortality. A decision was then made to allow the area to naturally revert to an even-aged bottomland hardwood stand.

Historic records of climate data show the growing season in Angelina County averages 244 days with the last freeze in the spring occurring around March 14 and the first freeze in the fall occurring around November 13 (Griffiths and others 1987). Winters tend to be mild with about 35 days where the temperature falls below 32 °F, and summers tend to be hot and humid with about 103 days where the temperature rises above 90 °F. The average annual daily maximum and minimum temperatures are 78 °F and 56 °F, respectively, and the mean annual precipitation is 41.5 inches, including about 65 days with 0.1 inches or more of precipitation (Griffiths and others 1987). According to Eyre (1980) the majority of this stand can be classified as the willow oak—water oak—diamond leaf (laurel) oak (*Quercus laurifolia* Michx.) (88) forest cover type, which is commonly described as a “pin oak flat.” Another important forest cover type that forms a component of the stand is the swamp chestnut oak—cherrybark oak (91) forest cover type (Eyre 1980). This is important to note because the statistical block design was applied in relation to where these specific forest cover types occurred on the landscape.

Experimental Design and Treatment Application

The study area included four replications (blocks). Each block was about 3 acres in size. Within each 3-acre block, there were six 0.5-acre, rectangular treatment plots. Within each 0.5-acre treatment plot, there was a 0.25-acre rectangular measurement plot surrounded by a 15-foot buffer strip, which was installed to limit the spread of fertilizer between measurement plots. The factorial arrangement of treatments for each of the 0.5-acre treatment plots is listed as follows: (1) crown-thinned and fertilized, (2) crown-thinned and unfertilized, (3) low-thinned and fertilized, (4) low-thinned and unfertilized, (5) unthinned and fertilized, and (6) unthinned and unfertilized (control). All were assigned randomly to each of the six treatment plots within each of the four blocks. The study was established in 1998 and pretreatment measurements were taken.

The selection of crop trees was accomplished using crown size, stem position, and crown classification. The crop-tree method was chosen because there is a need to place more attention on individual trees within bottomland hardwood stands. Smith and Long (2001) stated that culmination of stand-level production invariably precedes, sometimes by decades, culmination of individual tree production. Furthermore, according to Stringer and others (1988), the crop-tree approach concentrates treatment benefits from intermediate treatments on trees with the highest potential to increase in value; in area-wide thinnings, trees are more likely to be removed without considering benefits to the residual stand.

When using the crop-tree method, Houston and others (1995) stated that a list of acceptable tree species and stem-quality classes must first be created. The tree-class system suggested in Meadows (1996) was used in selecting crop trees for the study, and the Kraft Crown Classification Method lists four crown positions: dominant, codominant, intermediate, and overtopped (suppressed). Crop-tree selection was limited to trees of the codominant or dominant crown classes in relation to spacing. Meadows and others (2001) stated that the four factors ultimately contributing to crown classification are amount of direct sunlight received from above, amount of direct sunlight received from the sides, crown balance, and relative crown size. When

the trees were marked in February 1999, ideas relating to the development of Meadows and others (2001) were well known and used in the selection of crop trees. All red oak trees that exhibited healthy crowns, exhibited or had the potential to develop a grade 1 butt log (Kenna 1981), had few to no epicormic branches on the butt log, and were free of disease were considered suitable crop trees. Other species were selected as crop trees when no suitable red oak species existed; this was done to uphold the thinning method applied and to maintain proper spacing.

Species favored for crop-tree selection were ranked as follows: (1) cherrybark oak, (2) water oak, (3) willow oak, (4) green ash, and (5) sweetgum. Crop trees were selected in the control plots as well as the treated plots. As previously defined, crown thinning consisted of removing trees from the dominant and codominant crown classes while leaving all trees within the intermediate and suppressed classes. During low thinning, only trees from the intermediate and suppressed crown classes were removed. When marking the stand for harvest, trees within the buffer strip were considered competition and recognized as pseudo-crop trees even though they were not measured as part of this study. This was done so that the observations in each measurement plot would not be biased and would be in keeping with the applied silvicultural treatments of crown and low thinning that were applied in early March 1999. During thinning treatments, trees were felled by chainsaw and left in place because of wet soil conditions.

Following the thinning treatments, a single application of granulated fertilizer yielding both nitrogen and phosphorous nutrients was applied to each of the plots randomly selected to receive fertilizer. The fertilization treatment was based on standard fertilization practices used in loblolly pine silviculture (Jokela and Stearns-Smith 1993) and is similar to fertilizer treatments used in upland hardwoods by Graney and Pope (1978). N was applied at the rate of 200 pounds per acre, and P was applied at the rate of 50 pounds per acre as ammonium nitrate (34-0-0) and diammonium phosphate (18-46-0), respectively. Hand-spreaders were used to apply the fertilizer in late June 1999, later than originally planned, due to early spring flooding at the study site.

Measurements

Prior to harvest, all trees within each 0.25-acre measurement plot were described as follows: (1) species; (2) d.b.h. (diameter at breast height, 4.5 feet above ground) of all trees > 3.5 inches (to the nearest 0.1 inch); (3) distance in feet from each tree center to plot center (recorded per 0.1 foot); (4) azimuth of each tree in relation to plot center; and (5) crown classification. Pretreatment measurements were taken in the winter of 1998-99. First-year measurements (after treatment) of tree d.b.h. were collected in December 1999. Second-year measurements of tree d.b.h. were taken in December 2000. Third-year measurements of tree d.b.h. were taken in December 2001.

Epicormic branching was also measured on each crop tree within each of the 24 measurement plots. It was measured from 0 to 17.5 feet high on the tree bole to assess butt log quality. All epicormic branches were categorized as < 1 foot or > 1 foot in length to assess the importance of log defect. This takes into account the fact that older, more established branches are a greater threat to log quality. All branches were tallied by length within each 1-foot height increment separately; they were also broken into two categories within each 1-foot height increment: > 1 foot (old) and < 1 foot (new). First-year epicormic data were collected to assess the 1999 growing season, second-year measurements were taken to assess the 2000 growing season, and third-year measurements were taken to assess the 2001 growing season. However, preharvest measurements of epicormic branching were not recorded.

Analyses

All statistical analyses were done with SAS Version 8 (SAS Institute 2000). The measurement unit was each tree, the experimental unit was each plot, and the sampling unit was the stand itself. Furthermore, this study was analyzed using a randomized complete block design. This was done appropriately through analysis of variance (ANOVA) with 3 degrees of freedom for blocking, 5 degrees of freedom for treatments, and 15 degrees of freedom for error, which makes 23 degrees of freedom total. Significant differences were reported through ANOVA when $p \leq 0.1$ in the initial F-test. Comparison between each of the separate treatments was analyzed using the Least Significant Difference (LSD) multiple pairwise comparison method.

Specifically, periodic annual increment (PAI) of mean diameter growth in 1999, 2000, and 2001 was evaluated through ANOVA to show the progression of cumulative growth according to treatment. For example, PAI in 2001 was calculated by taking each tree's diameter measurement in 2001 (x_3), subtracting each tree's pre-treatment diameter measurement (x_{pre}), and then dividing that quantity by 3 to represent the period (third-year) that the measurement was taken: $(x_3 - x_{pre})/3$. For the final step in figuring PAI, the value for each tree was then totaled to calculate the periodic mean growth. Then, current annual increment (CAI) of mean diameter growth was evaluated each year using a repeated-measures ANOVA. This was essentially mean growth within each of the 3 years of 1999, 2000, and 2001, showing the contribution of each year's growth toward PAI. For example, CAI in 2001 was calculated by taking each tree's diameter measurement in 2001 (x_3) and subtracting each tree's diameter measurement in 2000 (x_2): $x_3 - x_2$. For the final step in figuring CAI, the value for each crop tree was then totaled to calculate the current year's mean growth. Epicormic branching values were also calculated by summing the mean number of epicormic branches by individual crop tree, block, plot, and branching category (< 1 foot or > 1 foot in length). Means were then compared by treatment and branching category using ANOVA and LSD pairwise comparisons.

RESULTS AND DISCUSSION

Crop Tree Diameter Growth Response

Among all trees, PAI of diameter growth in 1999 and 2000 was significantly greater in unthinned plots than in thinned plots (table 1). This was most likely due to the removal of trees in thinned plots because there were always less trees per acre in thinned plots than in unthinned plots. No difference in PAI of crop trees was noted until 2000 and

Table 1—PAI diameter growth of all trees and crop trees by treatment and year, where values in parentheses represent standard error, and means with the same letter are not significantly different

Trees	Treatments	1999 PAI	2000 PAI	2001 PAI
		inches		
All trees	Crown	0.10 (< 0.01) b	0.12 (0.01) b	0.15 (0.01)
	Low	0.12 (0.01) b	0.13 (0.01) b	0.13 (0.01)
	No	0.14 (0.01)a	0.14 (0.01) a	0.14 (0.01)
Pr > F		0.01	0.03	0.37
Crop trees	Crown	0.30 (0.02)	0.38 (0.02) a	0.44 (0.02) a
	Low	0.32 (0.03)	0.39 (0.05) a	0.38 (0.03) a
	No	0.29 (0.01)	0.30 (0.01) b	0.32 (0.01) b
Pr > F		0.13	0.06	0.01
All trees	Fertilized	0.12 (0.01)	0.13 (0.01)	0.14 (0.01)
	Unfertilized	0.12 (0.01)	0.13 (< 0.01)	0.14 (< 0.01)
Pr > F		0.67	0.48	0.26
Crop trees	Fertilized	0.28 (0.02)	0.34 (0.02)	0.38 (0.02)
	Unfertilized	0.33 (0.02)	0.37 (0.03)	0.38 (0.03)
Pr > F		0.13	0.33	0.78

PAI = periodic annual increment.

2001 when crop trees in thinned plots achieved significantly greater diameter growth than crop trees in unthinned plots. The growth of all trees preceding the growth of crop trees may be a case of stand level growth preceding individual tree level growth after thinning (Feduccia 1979, Feduccia and Mann 1976, Long 1985, Smith and Long 2001).

Furthermore, results of CAI showed that diameter growth of all trees in 1999 was better in unthinned plots than in thinned plots (table 2), which may be caused by greater basal area per acre in unthinned plots than in thinned plots. In 2000, CAI diameter growth of crop trees in thinned plots was significantly greater than CAI diameter growth of crop trees in unthinned plots. Most importantly, 2001 CAI diameter growth of crop trees in crown-thinned plots was greater than CAI diameter growth of crop trees in either low-thinned or unthinned plots. The diameter-growth responses to thinning found in this study are typical of many studies (Feduccia 1979; Graney 1987; Graney and Pope 1978; Johnson 1968; Johnson and McKnight 1969; Lambert 1957; Langsaeter 1941; Meadows and Goelz 1993, 1999, 2001; Schaertl and others 1997; Scott and others 2001; Stone 1977; Stringer and Wittwer 1985; Stringer and others 1988), but no study was found that specifically compared crown thinning and low thinning in bottomland hardwoods.

Table 2—CAI diameter growth of all trees and crop trees by treatment and year where values in parentheses represent standard error, and means with the same letter are not significantly different

Trees	Treatments	1999 CAI	2000 CAI	2001 CAI
		inches		
All trees	Crown	0.10 (< 0.01) b	0.15 (0.01)	0.20 (0.02)
	Low	0.12 (0.01) b	0.15 (0.01)	0.15 (0.02)
	No	0.14 (0.01)a	0.15 (0.01)	0.17 (0.02)
Pr > F		< 0.01	0.26	0.14
Crop trees	Crown	0.30 (0.02)	0.47 (0.02) a	0.55 (0.05) a
	Low	0.32 (0.03)	0.45 (0.06) a	0.38 (0.04) b
	No	0.29 (0.01)	0.31 (0.02) b	0.36 (0.03) b
Pr > F		0.13	0.02	< 0.01
All trees	Fertilized	0.12 (0.01)	0.15 (0.01)	0.18 (0.02)
	Unfertilized	0.12 (0.01)	0.15 (0.01)	0.16 (0.02)
Pr > F		0.67	0.26	0.47
Crop trees	Fertilized	0.28 (0.02)	0.40 (0.03)	0.45 (0.03)
	Unfertilized	0.33 (0.02)	0.42 (0.05)	0.42 (0.05)
Pr > F		0.13	0.67	0.43

CAI = current annual increment.

Epicormic Branching Response of Crop Trees

Mean number of all epicormic branches regardless of length only showed a difference in 2000 where crop trees in crown-thinned plots had more epicormic branches than crop trees in unthinned plots (table 3). This is most likely due to a greater amount of sunlight reaching tree boles in crown-thinned plots (Meadows 1995). In 2000, crop trees in fertilized plots also had significantly more epicormic branches than crop trees in unfertilized plots (table 3).

Mean number of epicormic branches according to branch length showed a difference in 2000 and 2001 where more epicormic branches >1 foot were found on crop trees in crown-thinned plots than in unthinned plots (table 4). Furthermore, in 1999, 2000, and 2001, more branches >1 foot occurred on crop trees in fertilized plots (table 4). In respect to thinning, these findings tend to contradict those of Meadows and Goelz (2001) who found that heavier thinning caused a minimal increase in epicormic branching among crop trees. They stated that retaining significant amounts of lower crown-class trees increased the risk of epicormic branching. However, findings in the present study upheld the findings of Chapin (1991) and Osmond and others (1987) who said that plants usually respond to an increase in stress by exhibiting a decrease in growth. Furthermore, Levitt (1980a, 1980b) defined biological stress as any change in environmental conditions that may reduce *or* adversely change a plant's growth or development. Levitt also distinguished between avoidance and tolerance of stress; during avoidance, the plant responds by attempting to reduce the impact of the stress factor (sometimes by growth), and during tolerance, the plant simply endures and survives the stress factor. Biological stress due to competition for nutrients and sunlight may be a cause of avoidance in the form of epicormic branching. Over all, there was a great decline in epicormic branches < 1 foot in 2000 and 2001 (table 4), which tends to indicate most new epicormic branches formed directly after thinning in crown-thinned and fertilized plots. Therefore, relatively few new branches have formed in 2000 and 2001, and those that formed after thinning are slowly dying back due to canopy closure.

Table 3—Mean number of all epicormic branches on crop trees by treatment and year, where values in parentheses represent standard error, and means with the same letter are not significantly different

Treatments	1999	2000	2001
Crown	24 (5)	16 (2)a	15 (2)
Low	22 (5)	11 (2)ab	11 (2)
No	17 (3)	8 (1)b	8 (1)
Pr > F	0.64	0.03	0.11
Fertilized	25 (4)	14 (2)a	13 (2)
Unfertilized	18 (2)	9 (1)b	10 (1)
Pr > F	0.64	0.02	0.11

CONCLUSIONS

Crop Tree Diameter Growth

A positive response in diameter growth of crop trees following both crown and low thinning was expected. This proved to be true when crop trees in thinned plots showed greater PAI diameter growth than unthinned plots in 2000 and 2001. Most notably, crown-thinned plots showed a greater CAI diameter-growth rate than both low-thinned and unthinned plots in 2001. A greater positive response in diameter growth of crop trees after crown thinning than after low thinning was also expected. This was only the case during 2001 measurements of CAI diameter growth. Furthermore, a greater positive response in diameter growth of crop trees in thinned and fertilized plots than in plots thinned alone was also expected. However, there was no diameter-growth response of crop trees due to fertilization treatment, which may be due to the current fertility of the soil. Under conditions of high mineral nutrient availability in soils, plants have a low potential to absorb mineral nutrients; therefore, nutrient demand by the plant has more effect on nutrient uptake than nutrient availability in the soil (Clarkson 1985). In other words, the crop trees in the present study could have already had enough nutrients when the fertilizer was applied.

Table 4—Mean number of epicormic branches on crop trees by treatment, year, and branch length, where values in parentheses represent standard error, and means with the same letter are not significantly different

Treatments	1999	1999	2000	2000	2001	2001
	< 1 foot	> 1 foot	< 1 foot	> 1 foot	< 1 foot	> 1 foot
Crown	13 (3)	11 (3)	2 (<1)	14 (2) a	2 (<1)	13 (2) a
Low	14 (4)	9 (2)	2 (<1)	9 (1) ab	2 (<1)	9 (1) ab
No	12 (2)	6 (1)	2 (<1)	7 (1) b	2 (<1)	6 (1) b
Pr > F	0.68	0.12	0.15	0.01	0.52	0.02
Fertilized	14 (3)	11 (2) a	2 (<1)	12 (2) a	2 (<1)	12 (2) a
Unfertilized	11 (2)	6 (1) b	2 (<1)	8 (1) b	2 (<1)	7 (<1) b
Pr > F	0.68	0.05	0.15	0.02	0.26	0.03

Epicormic Branching

Thinning and fertilization were expected to decrease the occurrence of epicormic branching on tree boles, but drawing conclusions regarding epicormic branching measurements was difficult due to the absence of pretreatment measurements. However, data from second-and third-year results suggested a need for further research in this area. Crop trees in crown-thinned plots showed a significantly greater number of epicormic branches > 1 foot in 2000 and 2001. Furthermore, crop trees in fertilized plots also showed a significantly greater number of epicormic branches > 1 foot in 1999, 2000, and 2001 measurements. However, there was a great decline in epicormic branches < 1 foot in 2000 and 2001, which indicated most new epicormic branches formed directly after thinning. There was also a decline in total number of epicormic branches between 1999 and 2000, which indicated that branches formed after thinning have begun to die.

ACKNOWLEDGMENTS

Initial funding was provided by Temple-Inland Forest Products Corporation, Diboll, Texas, and the Arkansas Forest Resources Center, University of Arkansas, Monticello, Arkansas. Stephanie Allison and Ralph Pearce, both of the USDA Forest Service, provided constructive comments on earlier versions of this manuscript.

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LEAF BIOMASS AND ACORN PRODUCTION IN A THINNED 30-YEAR-OLD CHERRYBARK OAK PLANTATION

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Abstract—Objectives of this study were to determine the effects of two levels of thinning on leaf biomass and acorn production of cherrybark oak (*Quercus pagoda* Raf.). To evaluate the effects of thinning 2 years after treatment, treatment plots were selected and blocked on the basis of initial stocking levels. Two levels of stocking and a control were established for each of five repetitions. Collection traps were randomly distributed on each plot to collect litter and acorns. The contents of the traps were collected weekly throughout the fall and winter of 2001. ANOVA was used to detect significant differences among thinning treatments regarding leaf biomass and acorn production. Two years after thinning, both leaf area and acorn production were affected by thinning level. Results, although preliminary, suggest enhanced leaf area and changes in acorn production. Level of thinning did have different effects over the short term.

INTRODUCTION

There were 5 million hectares of forested land in Louisiana in 1991. This accounted for 52.5 percent of the total land area of the State. Of the forested land, 62 percent was owned by nonindustrial private landowners, 29 percent belonged to the forest products industry, and 9 percent was publicly owned. Bottomland hardwoods made up 34 percent of this land (Vissage and others 1992). Good hardwood management can therefore have significant impact on both economic and habitat-related factors in Louisiana.

One of the more important bottomland hardwood species in the lower Mississippi Valley is cherrybark oak (*Quercus pagoda* RAF). It is plentiful in this region where it grows quickly, generally producing a clear bole and superior quality wood. These qualities have led to its being rated the best red oak in the region; it is used for furniture and trim (Harlow and others 1996).

Knowledge of the effects of thinning on acorn production could be useful on several fronts. Cherrybark oak acorns are important both as a source for regeneration and as food for wildlife (Auchmoody and others 1993); the acorns provide vitamins, fats, and carbohydrates for deer, squirrels, mice, ducks, and turkeys (Kea 1999). Acorns can also be harvested and used by nurseries to grow seedlings. Thinning is a commonly used stand management tool. A stand is typically thinned to a density that will meet landowner objectives, which can include increasing future timber value, improving stand and tree quality, producing current income, and enhancing wildlife habitat (Goodrum and others 1971). Management for wildlife includes ensuring that proper habitat is available and that food is readily obtainable. However, there is not much information available regarding the effects that thinning may have on bottomland hardwood plantations (Meadows and Goelz 2001). Similarly, there is little data about the effect thinning may have on acorn production (Healy 1997).

Biomass allocation has a great effect on the growth and physiology of a tree (Martin and others 1998). Since stem biomass and biomass allocation are dependent on solar energy capture and conversion, biomass production is closely related to leaf area. Understanding the nature of thinning effects on leaf biomass over time will be crucial in understanding the relationship between changes in stand density, stand productivity, and acorn biomass production.

MATERIALS AND METHODS

Study Site

This study took place on the Red River Wildlife Management Area (RRWMA) in Concordia Parish, LA. The portion of the RRWMA used for this study was one of a series of bottomland hardwood plantations located near the Mississippi River. The two growing seasons before this study were much drier than normal, with approximately 122 cm of precipitation compared with the average of 165 cm (Louisiana Office of State Climatology 2000, 2001). Precipitation during the study year was near normal, but nearly 51 cm of that came with tropical storm Allison that impacted the area from June 5-11, 2001. We did not see substantial storm damage at the site, but rainfall was high during that period. The soil on the site is of the Commerce-Bruin soil association. Cherrybark oak site index on the area averaged 33.5 m at base age 50. A 142.5-ha tract in the area north of State Highway LA910 was planted between 1969 and 1972. Various hardwood species were planted in single species blocks repeated throughout the area. Cherrybark oak accounted for approximately 43 percent of the planted area. Average planting density was 166 trees per ha.

Plot Establishment

Fifteen plots were established in 1998 in this plantation for an ongoing thinning study. The rectangular plots measured 20.4 by 81.6 m and were surrounded by a buffer strip 20.4 m wide. Diameters of trees greater than 12.88 cm at breast height (d.b.h.) were measured. Measurements were

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

used to determine initial stocking, which was based on Goelz's (1995) stocking guide for southern bottomland hardwoods. Five blocks, with three plots per block, were created based on initial stocking. One of three different thinning treatments was randomly assigned a plot within each block. The treatments were:

Treatment 1: Thin to a 70- to 75-percent stocking level

Treatment 2: Thin to a 50- to 55-percent stocking level

Treatment 3: Uncut control.

Once the plots were established, trees to be removed were selected based on d.b.h., crown class, vigor, and overall stocking. The Meadows and others (2001) crown classification system was used to evaluate crown condition, crown class, and vigor. Plots were thinned in the winter between 30 September 1998 and 03 February 1999. Thinning was a mixture between high and low thinning, but dominant and co-dominant trees were favored as leave trees.

Litter Trap Construction, Placement, and Collection

Leaf and acorn collection traps (hereafter referred to as traps) were constructed of shade cloth, plastic tubing, and PVC pipe. Circular traps, used to determine tree-level effects, were 1.0 m tall and 0.5 m^2 in area. Shade cloth sewn into a funnel shape was attached to plastic tubing formed into a circle, then attached to legs made of PVC pipe. A 5-gallon bucket (In a minimal number of cases, large pecan pots were used in place of 5-gallon buckets. The pots had holes in the bottom sides that were plugged with cotton; however, the cotton came out in some instances. Although we were careful to collect acorns that might have spilled, we could not determine if mice might have entered the holes and taken acorns. Mice feces were not found in the pots during the collections.) placed under each trap was used to collect acorns and leaves. Traps were stabilized by pushing the PVC legs into the ground. Holes were drilled into the buckets to allow rainwater to escape.

To test the effects of tree size and thinning level on the production of leaf biomass and acorns, a random selection of 48 trees was made in each of the three treatments for a total of 144 trees. A cardinal direction was randomly chosen, and the distance from the trunk of each sample tree to the edge of the crown was measured. A single trap was placed at a point halfway between the tree bole and the edge of the crown (Perry and Thill 1999).

Rectangular traps were also placed in the measurement plots and were used to estimate production of leaf biomass and acorn production for the entire plot. Elongated traps were made with PVC frames and had shade cloth attached to the frames with wire ties. Elongated traps were 3.04 m long, 0.609 m wide, and 1.85 m^2 in area. Twelve traps were placed on each plot to represent a 1-percent sample of the plot area (168 total rectangular traps). A randomly chosen row and distance into the plot were chosen as the placement point for a rectangular trap, and a random distance from the tree boles within a row was also chosen for the placement between rows. This sampling scheme was designed to effectively sample the entire area, not just areas under tree crowns. The traps were emptied once a week during the period of acorn and litter fall (approximately mid-October to December). When the litter and acorn fall decreased, traps were emptied every 2 weeks, with the final collection completed the first week of February.

Analysis

All leaf litter and acorns were transported to the lab. Litter was sorted and all non-cherrybark litter was removed. Cherrybark oak leaf litter and acorns were oven-dried and weighed. All materials were dried until stable ovendried weights were achieved. Both leaf litter biomass and acorn biomass results were analyzed using ANOVA and Tukey's Studentized Range tests (SAS 1991). A significance level of 0.05 was chosen as adequate to show significant differences in this study.

RESULTS

Leaf Biomass

When analyzed at the individual tree level (circular traps), trees in the light-thinned treatment produced the greatest amount of leaf biomass, 22.7 g per m^2 of trap area, whereas trees in both the unthinned control treatment and the heavy-thin treatment produced only 17.5 g per m^2 and 15.6 g per m^2, respectively (fig. 1). There were significant differences ($\alpha = 0.05$) in leaf biomass produced between the control treatment and the light-thin and between the light and heavy-thin treatment. There were no significant differences between the leaf biomass collected in the control plots and the heavy-thin treatment plots.

On a whole-plot basis (rectangular traps), the light-thin treatment also produced the greatest amount of leaf biomass, 284.3 kg per ha, followed by the control, 243.2 kg per ha, and the heavy-thin, 211.0 kg per ha (fig. 2). Only

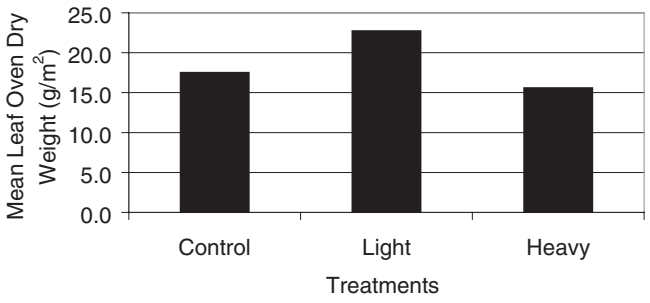

Figure 1—Mean leaf biomass per unit trap area collected midway between tree bole and canopy edge.

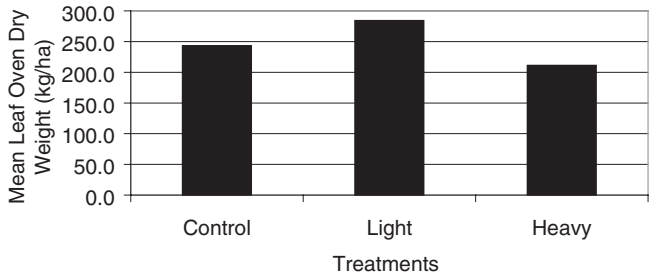

Figure 2—Mean leaf biomass collected per unit plot area.

contrasts between the light-thin and heavy-thin treatments produced significant differences in leaf biomass. No significant differences existed between the control and light-thin, or the control and heavy-thin.

Acorn Biomass

For purposes of this paper, all acorn biomass, complete acorns, acorn caps, and acorn pieces were weighed together. Means of 3.0, 2.2, and 1.6 g per m^2 of acorn biomass were collected on the control, light-thin, and heavy-thin treatments, respectively (fig. 3). Significant differences ($\alpha = 0.05$) were found between the control and the heavy-thin treatment. There were no significant differences between the control and the light-thin treatment or the light-thin and heavy-thin treatments.

Means of 14.1, 8.1, and 8.1 kg per ha of acorn biomass were collected in the rectangular traps in the light-thin treatment, control, and heavy-thin treatments, respectively (fig. 4). No significant differences were found between any of the treatments.

DISCUSSION

Tree Level Measurements

Light thinning appeared to have the greatest early effect on leaf biomass production at the individual tree level. There were significant differences between the light-thin treatment and both the heavy-thin and control treatments. The lack of response on the heavy-thin could be due to reductions in relative tree size on heavy-thinned plots or could be the result of slow crown expansion caused by an initial shock from the heavy-thin treatments (Johnson and others 2002). The crowns of the light-thin treatment could be increasing at a slightly greater rate than those of the heavy-thin treatment. Greater crown expansion would result in a greater leaf area, which would promote greater biomass production by allowing for greater rates of photosynthesis (Johnson and others 2002).

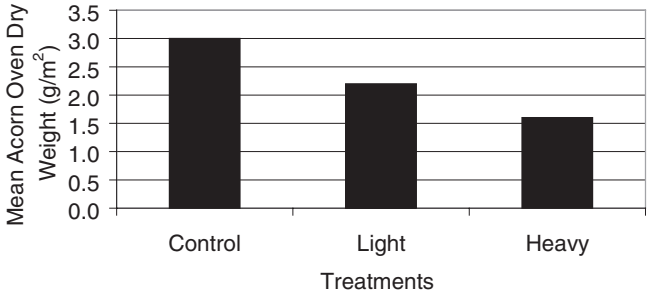

Figure 3—Mean acorn biomass per unit trap area collected midway between tree bole and canopy edge.

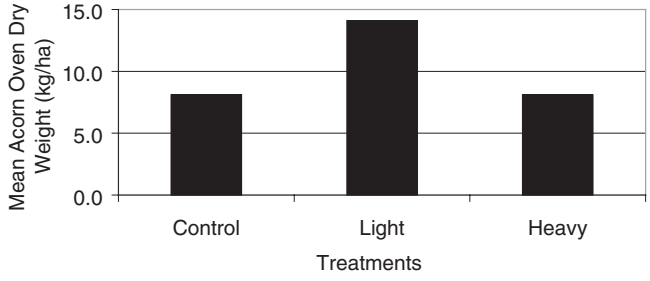

Figure 4—Mean acorn biomass collected per unit plot area.

On an individual tree level, both the light-thin and the control treatment produced significantly more acorn biomass than the heavy-thin treatment. In contrast, Healy and others (1999) found that trees in thinned plots produced more acorns than those in unthinned plots. We found variation in acorn production among individual trees to be high. Healy (1997) also found variation in individual trees to be greater than the effect of thinning. Continuing study of the results over time may lead to firmer conclusions.

Plot Level Measurements

Thinning also affected leaf biomass production at the plot level. Two years after treatment, leaf biomass production in the light-thin plots was 34 percent greater than that in the heavy-thinned plots, but there was no significant difference in leaf biomass production between the light-thin and the control or the heavy-thin and the control. Light thinning seemed to stimulate leaf biomass production at the plot level as well as at the individual tree level. This is most likely the result of crown expansion into the newly opened gaps in the canopy. This growth in turn increases leaf area, which increases tree-level photosynthetic capacity (Johnson and others 2002). The heavy-thin treatment removed considerable basal area, more trees, and more leaf area from the plots. Time needed to recover lost leaf area will likely take longer in the heavy-thin treatment. Since heavy-thinned plot leaf biomass production was not significantly different from leaf biomass on the unthinned control plots, it appeared that leaf biomass production may have been stimulated by the heavy thinning as well. At the time of the study, the crowns in the light and heavy-thin treatments may still have been expanding at the same rate. This would cause the light-thin to produce more biomass because there are more trees in the light-thin treatments than the heavy-thin. Further analysis is warranted.

At the plot level, there was no significant difference in acorn production. This may be the result of several factors. It may be too soon to see the effects of thinning on acorn production. The acorn crop produced the year of this study was relatively small and may have been a product of the previous 2 low-precipitation years plus the effects of tropical storm Allison that hit the area in early June. Predation may also have affected the amount of acorns collected in the traps.

Further Research

Initially, it appeared that a light-thin treatment would increase the leaf biomass and acorns produced in a stand within 2 years after a thinning operation. A heavy-thin might appear to have a negative impact on both leaf and acorn production; however, there was no significant reduction of leaf biomass at the plot or the tree level, nor was there a reduction in acorn production at the plot level when compared to the unthinned control. The heavy-thin treatment and control appeared to produce leaf biomass and acorns in the same

amount, despite the heavy-thin plots having fewer and somewhat smaller trees. This indicated greater production per tree on the heavy-thinned plots than on the controls. The longer term effects of thinning may, indeed, show a large enhancement in leaf and acorn biomass with heavier thinning levels on these good sites. The next few years of data collection and analysis will be useful in revealing the response to the heavier thinning treatment.

ACKNOWLEDGMENTS

The authors would like to thank the Louisiana Department of Wildlife and Fisheries for their support with the cherry-bark oak thinning study. We would also like to thank Luben Dimov, Andrew Gross, Melinda Hughes, Dr. Brian Lockhart, Kristi Wharton, and Joy Young for their help in the field and the lab. We thank Dr. Paul Burns, Dr. Quang Cao, and Joy Young for reviewing the manuscript. We gratefully acknowledge the McIntire-Stennis Cooperative Forestry Act and the Gilbert Fellowship Foundation Program in the School of Renewable Natural Resources for partially funding this research effort. Approved for publication by the LSU AgCenter as manuscript number 03-40-1237.

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DETERMINING STOCKING LEVELS IN YOUNG, MIXED HARDWOOD STANDS IN THE NORTH CAROLINA PIEDMONT

Jamie L. Schuler and Daniel J. Robison[1]

Abstract—Upland Piedmont hardwood stands represent an important forest type in North Carolina and the Southeastern United States. Many of these forests are being converted to other land uses. A solution to maintaining these forest types lies in increasing productivity and profitability of this resource. This implies a shift from traditional, extensive management to more intensive silviculture, including pre-commercial thinning. However, there is a lack of information available to managers for assessing stocking levels and to guide decisionmaking in these upland stands. A preliminarily model for identifying full stocking is presented.

INTRODUCTION

Forest managers are continually seeking ways to increase production and efficiency of forests. Southern hardwoods are generally managed under an even-aged silvicultural system, with clearcutting often prescribed as the regeneration method. Even-aged regeneration methods commonly regenerate 10,000 to 40,000 stems per acre (Johnson and Krinard 1988, Romagosa and Robison 2003, Young and others 1993). Given that current rotations produce a few hundred harvestable stems per acre, it seems apparent that 10,000 or more stems per acre at establishment is well overstocked.

Density reductions through release cuttings and precommercial thinnings have been shown to increase diameter growth (Miller 2000), height growth (Schuler and Robison 2002), both height and diameter growth (Johnson and others 1997, Newton and others 2002), and, in some instances, neither (Trimble 1973). However, as Kochenderfer and others (2001) note, the greatest gains in value arise from improved species composition following thinnings.

Works by Kellison and others (1981), Resovsky (1984), and others have indicated that many Piedmont mixed hardwood stands are largely overstocked. Thinning trials have been installed on a variety of sites in the South, often without specific understanding of relative density and the effects of species composition as stands age (Roach 1977, Stout and Nyland 1986). Chisman and Schumacher (1940) illustrated the species effect in their classic work on tree-area ratios. In their example, they showed that pines and hardwoods occupied different amounts of space as a function of diameter.

Traditional theories of stand regulation advocate holding stand-level stocking at a point where individual tree growth is optimized while still fully occupying the site. This level is commonly termed the B-line on stocking guidelines. Even at 1 to 3 years of age, southern hardwood stands have been shown to respond to precommercial thinning (Schuler and Robison 2002). However, information on desirable stocking levels (i.e., 70 percent versus 100 percent) in young stands remains sparse.

Stocking guides have been produced for a number of forest types and species throughout the United States, and some developed elsewhere are being applied in upland Piedmont stands (Gingrich 1967). None have been developed specifically for young upland Piedmont hardwoods.

Most stocking adjustments in stands less than pole-sized are performed using a best guess approach to residual stocking because there are no guidelines presently available. Existing stocking guides do not provide information on trees less than 3 inches in d.b.h. (Gingrich 1967). Without guidelines to judge the relative level of stand density, these treatments may be ineffective, detrimental, or, at least, inconsistent. This research provides a preliminary guide to relative stocking levels for young natural, mixed hardwood stands in the Piedmont as part of an ongoing effort to understand stand dynamics of these sites.

METHODS

We inventoried 46 plots in upland Piedmont mixed hardwood stands in North Carolina, recording species and diameter of individual stems greater than breast height to provide the basis for estimating the A-line (100 percent stocking). Plot size was variable depending on average tree size, which ranged from about 0.3 to 6 inches quadratic stand diameter (QSD). Plots were selected based on the following criteria:

1. Free-growing since regeneration (e.g., clearcut)
2. Composed of commercially valuable species
3. No indication of disturbance (e.g., wind throw)
4. No silvicultural treatments since stand establishment
5. Apparent full stocking (e.g., obvious mortality present).

The A-line was estimated by two techniques, first by using the classic tree area ratio (TAR) method (Chisman and Schumacher (1940):

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Tree Area (milacres) = $B_0(N) + B_1(\Sigma D) + B_2(\Sigma(D^2))$, (1)

where N and D represent number of stems per unit area and diameter (in inches), respectively, and B_0, B_1, B_2 are regression coefficients.

Secondly, a modification of the TAR by Roach (1977) and Stout and Nyland (1986) was used, which includes a technique to account for species composition:

Tree Area (milacres) = $\Sigma_i (B_{oi} N_i + B_{1i} \Sigma_j D_{ij} + B_{2i} \Sigma D^2_{ij})$, (2)

where N_i is the number of trees per unit area of the i^{th} species, D_{ij} is the diameter of the j^{th} tree of the i^{th} species on the plot, and B_{oi}, B_{1i}, and B_{2i} are regression coefficients.

RESULTS AND DISCUSSION

The TAR model for all species combined fit the data reasonably well (r^2=0.88), but with some dispersion of data points (fig. 1). Fit improved greatly when a species composition component with 5 groups was included (table 1; r^2 = 0.96). Species groups were selected to be consistent with the North Carolina State University Hardwood Research Cooperative growth and yield model for southern hardwoods (work in progress). Quadratic mean diameters represented in both models ranged from about 0.3 to 6 inches. Parameter estimates are listed in table 2.

The predicted stocking level for the combined species model averaged 92 percent with a standard deviation over 35 percent. Accuracy of the predicted stocking levels for the species group model was improved, where stocking averaged 96 percent with a standard deviation less than 20 percent. This model, which included species groups, improved predictions by accounting for differences in growing space requirements of various species groups. There were substantial differences in growing space needs depending on species composition, e.g., yellow-poplar (A) versus white oak (C) groups (fig. 2). The hickory species group (D) behaved much differently than the others. Its shape was more parabolic over the range of data, which we were unable to explain at this time. Nonetheless, since hickory has such a small component in these stands, its impact was probably minimal on the overall model.

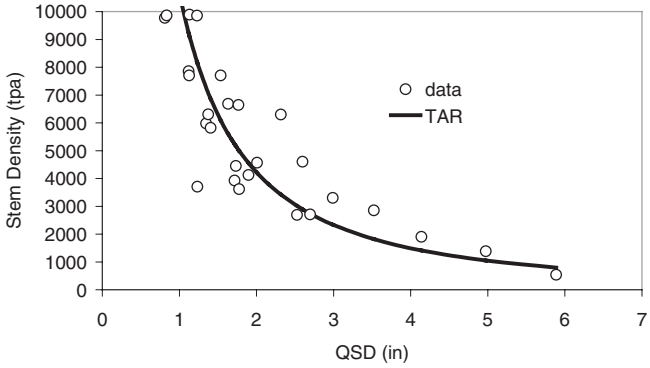

Figure 1—Stem-density predictions using combined species TAR model. Note that data less than 1 inch was not shown for illustration purposes.

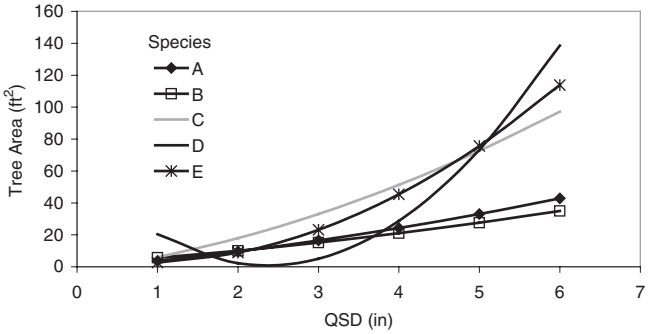

Figure 2—Tree-area curves for different species groups showing the growing space requirement under full stocking conditions. Members of each species group are identified in table 1.

Table 1—Species groupings used for TAR equation and compositional breakdown for selected Piedmont forest stands

Species group	Percent basal area of all plots	Included species
A	51.9	Yellow-poplar (*Liriodendron tulipifera* L.), sweetgum (*Liquidambar straciflua* L.), blackgum (*Nyssa sylvatica* Marsh.), and red maple (*Acer rubrum* L.)
B	24.4	Red oak[a] (*Quercus rubra* L.), redbud (*Cercis canadensis* L.), ash (*Fraxinus* spp.), elm (*Ulmus* spp.), and pine (*Pinus* spp.)
C	6.3	White oak[b] (*Q. alba* L.), black cherry (*Prunus serotina* Ehrh.), sycamore (*Platanus occidentalis* L.)
D	3.1	Hickory (*Carya* spp.), willow oak (*Q. phellos* L.)
E	14.3	Miscellaneous, mainly dogwood (*Cornus florida* L.), and all others

TAR = tree area ratio.

[a] Includes black oak (*Q. velutina* Lamarck), scarlet oak (*Q. coccinea* Muench.), S. red oak (*Q. falcata* Michx.)

[b] Includes post oak, (*Q. stellata* Wang.) and chestnut oak (*Q. prinus* L.).

Table 2—Parameter estimates for TAR model for combined species and species-grouped models

Parameter	Combined species	Species-grouped model				
		A	B	C	D	E
B_0	0.02863	-0.0296	0.0408	-0.0694	1.3601	0.1014
B_1	0.04908	0.1027	0.0740	0.1686	-1.1331	-0.1314
B_2	0.02727	0.0110	0.0086	0.0358	0.2394	0.0917

TAR = tree area ratio.

Other stocking guides developed specifically for use in this region (Brenneman 1983), or those often applied (Gingrich 1967) generally predict densities much lower than those suggested here. This may be due to tallied size-class differences among guides. Our tallies included all stems greater than breast height. The Gingrich guide starts at 1-inch d.b.h., whereass others focus on merchantable size classes and ignore small stems.

The utility of the approach here is that it can be applied to young stands with smaller stems and higher densities than current stocking guides accommodate. Foresters may use this type of guide to determine percent stocking and whether stands have attained desired density or to make informed density control decisions for precommercial treatments.

ACKNOWLEDGMENTS

David Gadd and Jim Bridges assisted with the field component of this work. Their help is gratefully acknowledged. Funding was provided by the members of the North Carolina State University Hardwood Research Cooperative.

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INDIVIDUAL TREE RELEASE AND ENRICHMENT PLANTING IN YOUNG NATURAL UPLAND HARDWOODS

Daniel J. Robison, Jamie L. Schuler, Larry Jervis, Joseph L. Cox and Peter J. Birks[1]

Abstract—Individual naturally regenerated trees of red oak, white oak, and yellow poplar in upland North Carolina Piedmont hardwood stands aged 1 to 13 were treated with mechanical clearing, herbicide of competition, and fertilization. These treatments produced significant changes in height and diameter growth 2 to 3 years posttreatment. Generally, height growth was negatively impacted by mechanical release alone, but diameter growth was enhanced by most treatments. Height growth partly compensated when mechanical release was coupled with herbicides or fertilization or both. On similar sites, with stands at age 1, red and white oak 1-0 bareroot seedlings were enrichment planted with weed mats and fertilization, and height and basal-diameter increment studied after 3 years. These seedlings planted into natural regeneration survived well and responded positively in height and basal-diameter increment growth. Implications of the findings for promoting desirable stocking of preferred species in even-aged natural hardwood systems are discussed.

INTRODUCTION

Regenerating rapidly growing natural hardwood timber stands of preferred species has become a substantial forestry challenge across Eastern North American uplands. In many situations, existing (preharvest) stands do not contain sufficient numbers or size or both of preferred advance regeneration such as oaks (*Quercus* spp.), to foster desirable species composition in the new stand. When desired species are present in sufficient numbers in the new stands, their growth is often slow and mortality high due to intense competition from herbaceous vegetation and from less preferred trees such as red maple (*Acer rubrum*), yellow-poplar (*Liriodendron tulipifera*), American beech (*Fagus grandifolia*) and sweetgum (*Liquidambar styraciflua*). These and other issues, and the underlying ecological constraints in regenerating desirable species, have and continue to be broadly addressed (Allen and Marquis 1970, Downs 1946, Hilt and Dale 1980, Johnson and others 1997, Kellison and others 1988, Loftis and McGee 1993, McGee and Loftis 1992, Newton and Robison 2001, Romagosa and Robison 2003, Schuler and Robison 2001).

In many situations, the challenge of regenerating fast-growing stands of desirable species has been addressed through the development of plantation systems. In Eastern North American hardwoods, this has not proved to be a robust solution, due in large part to problems associated with weed/competition control. Furthermore, the genetic improvement of hardwoods has lagged, making plantations of hardwoods with poor growth rates and ineffective broadscale weed control doubly unattractive. For oaks in particular, genetic improvement has been very slow owing to relatively long juvenile periods, episodic seed crops, and abundant seed predators. Improvement is also costly, especially when adequate competition management options do not exist to help recoup the investments in genetic improvement.

In this study, we report on two postharvest techniques to affect species composition and growth rates in naturally regenerating hardwood stands. We have addressed these possibilities in young stands, ranging from 1 to 13 years, in order to discover new ways to (1) promote desirable natural regeneration regardless of composition and competition issues and (2) insert small planting stock into regenerating stands to enrich species composition. The former approach is analogous to crop-tree release, but in very young stands before natural processes have promoted individual stems into obvious crop-tree candidates (= "*crop tree release before they can be identified as crop trees*"). The later approach is an attempt to develop a plantation system on an individual tree basis within the broader context of a naturally regenerating stand (= "*an individual tree plantation, one tree at a time*").

METHODS

Individual Tree-Release Study

In 1998 on the North Carolina State University, Department of Forestry's Hill Demonstration Forest (Durham County) in the Piedmont region, three upland hardwood stands on similar sites, regenerated by clearcutting 6, 8 and 13 years previously, were selected. The two dominate species in the 6-year-old stand [mean height 3.3 feet, density 13,499 trees per acre (TPA)] were yellow poplar, then red oaks, and mixed others; in the 8-year-old stand (mean height 7.0 feet, density 15,200 TPA) dominants were yellow poplar, mixed other, and then red oaks; in the 13-year-old stand (mean height 13.8 feet, density 5,305 TPA) dominants were mixed others, then yellow poplar and red oaks.

About 70 non-stump-sprout-origin trees of northern red (*Quercus rubra*) or black oak (*Q. velutina*), white oak (*Q. alba*), and yellow poplar, in a dominant/codominant position, were identified on about a 20 foot by 20 foot grid (ca. 210 trees per site). Approximately equal numbers of trees of each species were randomly treated as:

1. Control
2. Mechanical = clearing of competition in 6-foot radius in Year 1 (1998)

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

3. Mechanical + Chemical Year 1 = clearing (Year 1) + Garlon on cut stumps in Year 2
4. Mechanical + Chemical Year 2 = clearing (Year 1) + Oust and Accord on competition in Year 2
5. Mechanical + Chemical Year 1 + Fertilization = clearing (Year 1) + Garlon (Year 1) + Fertilization (Yr 2) with DAP at 10 ounces per tree (90 N, 100 P, pounds per acre equivalent).

Tree height and d.b.h. were recorded in midsummer 1998, height remeasured after the 2000 growing season (2.5-year increment), and d.b.h. remeasured after the 2001 growing season (3.5-year increment).

Enrichment Planting and Release Study

One site each on the NC State University Department of Forestry's Hill Demonstration Forest and Schenck Memorial Forest (Wake County), both in the NC Piedmont, were identified and salvage-clearcut harvested during winter 1996-97 following damage from Hurricane Fran (Sept. 6, 1996). Stands naturally regenerated to mixed pine-hardwood. Into the two sites, a total of 216, 1-0 bareroot seedlings of northern red oak and white oak from a Georgia State nursery and the same number from a Virginia State nursery were shovel planted in February 1998 (864 trees total). Additionally, across the two sites, a total of 76 naturally regenerated seedling or seedling-sprout origin mixed oaks were identified for the study. Approximately equal numbers of all these tree types were randomly treated as:

1. Control
2. Fertilized = Fertilization with 1.75 ounces DAP per Tree in Year 1 (1998)
3. Weed Mat = 3 foot x 3 foot "Vis Pore" Weed Mat around Tree in Year 1
4. Fertilized + Weed Mat = Fertilizer + Weed Mat as above in Year 1.

Immediately after planting the height and basal diameter (BD) of each tree were measured and remeasured during winter 2000-01 (3-year increment). For both studies, blocking effects were not significant. For the enrichment planting study, site effects were not significant, and each tree was considered an individual-tree plot for statistical analysis by ANOVA (Analytical Software 2000). ANOVA P values less than 0.10 were considered significant, and those between 0.1 and 0.20 were considered indicative of a potentially substantive/emerging response in these early results.

RESULTS AND DISCUSSION

Findings in this study suggest that individual tree release and treatment of naturally regenerated red oaks, white oaks, and yellow poplar at ages 6, 8 and 13 years on these Piedmont sites, resulted in significant growth rate changes after 2 to 3 years (table 1). In nearly every case, the height growth of these trees was slowed by mechanical release but partly compensated for in red oak and yellow poplar when mechanical release was supplemented with chemical competition control or fertilization or both. This finding suggests that the relaxation of above ground crowding and competition for sunlight reduced the rate of height growth required to maintain canopy dominance. However, reductions in below ground competition (due to the chemical release treatments), or the improvement of microsite fertility (fertilization) or both, maintained height growth.

Unlike height growth, diameter growth was generally accelerated by the various treatments, for all species (table 1). These early responses suggest that tree-diameter growth alone can be enhanced by simple mechanical clearing around individual trees within dense, regenerating stands. However, this simple release in the absence of below ground competition control or fertility enhancement or both also resulted in slowed height growth. Although it is too early to determine the rotation-length impact of slowed height growth, if it is long-lived, then it would put these trees at a distinct size disadvantage despite any short-term increase in diameter growth. As canopy closure occurs and released trees respond with accelerated height growth, then the loss may be negated. Coupling mechanical release with chemical or fertility treatments or both appears to promote diameter growth and compensate in part for the reduction in height growth.

Enrichment planting of red and white oaks on these Piedmont sites was successful, with survival after 3 years greater than 90 percent among the red and white oaks across all treatments. Where height growth of enrichment-planted red and white oak seedlings responded significantly to the treatments, it was enhanced variably by the weed mats and fertilization and the combination of these treatments (table 2). Similar results were found for basal diameter-growth response of the planted seedlings. When significant, the data from these early measurements suggest that the weed mat effect may be greater than the fertilizer effect. The naturally regenerated mixed oak species, which were treated similarly to the enrichment-planted seedlings, responded more consistently than planted trees (table 2). It was the fertilization treatment that enhanced both height and BD growth of these natural oaks. These small natural trees, despite being of similar size to the planted seedlings at the start of the study, grew considerably more than the planted trees. This may be a reflection of their preadaptation to the site, or the fact that some substantial portion of these arose from advance regeneration, or both.

The putatively 1-year-old naturally regenerated oaks released at the same time as the enrichment-planted seedlings (table 2) are in essence a young age class of the study results reported in table 1. Together, these results suggest that naturally regenerated oak stems, at ages 1 to 13, can be made to grow more quickly with appropriate treatments. Treatments may vary with tree age. Other workers have reported similar findings (Allen and Marquis 1970, Beck 1977, Church 1955, Della-Bianca 1975, Hilt and Dale 1980, Lamson and others 1990, Smith and Lamson 1983). This approach to "crop tree release before individuals can be identified as crop trees" may hold substantial promise for altering species composition and growth rates of select stems in naturally regenerated hardwoods. Current research encourages the presence of a sizeable amount of advance regeneration oaks in order to ensure adequate oak stocking following overstory harvest

Table 1—Mean incremental growth response of individually released stems (non-stump-sprout origin) in young Piedmont natural hardwoods following clearcut regeneration at Hill Forest, NC

Treatments, and ANOVA *P*-value	Stand age when treatments were applied					
	2–5-year-height increment			3–5-year-d.b.h. increment		
	6	8	13	6	8	13
	feet			*inches*		
Red oak						
Control	3.4	3.2	4.0	0.39	0.38	0.48
Mechanical	2.8	2.3	3.7	0.53	0.44	0.65
Mech. + Yr 1 chemical	2.7	2.0	4.1	0.54	0.49	0.69
Mech. + Yr 2 chemical	2.3	2.9	4.1	0.55	0.63	0.67
Mech. + Yr 1 chem. + fert.	3.3	2.2	2.6	0.78	0.47	0.66
ANOVA *P*-value ≤	0.1	NS	NS	0.05	0.1	0.1
White oak						
Control	3.9	4.0	3.1	0.53	0.46	0.48
Mechanical	2.8	2.8	4.1	0.66	0.58	0.67
Mech. + Yr 1 chemical	2.8	2.2	2.8	0.72	0.64	0.58
Mech. + Yr 2 chemical	2.7	3.2	3.0	0.75	0.72	0.69
Mech. + Yr 1 chem. + fert.	3.3	2.8	2.8	0.8	0.68	0.72
ANOVA *P*-value ≤	0.05	0.05	NS	0.1	0.1	NS
Yellow poplar						
Control	3.0	4.0	4.3	0.28	0.46	0.45
Mechanical	2.6	2.6	2.6	0.46	0.50	0.48
Mech. + Yr 1 chemical	2.6	2.7	5.3	0.56	0.54	0.72
Mech. + Yr 2 chemical	2.8	3.8	4.0	0.48	0.54	0.54
Mech. + Yr 1 chem. + fert.	2.6	3.2	3.2	0.43	0.57	0.49
ANOVA *P*-value ≤	NS	0.1	0.1	0.05	NS	NS

NS = not significant.

Table 2—Mean 3-year (1998–2000) incremental growth response of planted (February 1998) bareroot seedlings and individually released naturally regenerated mixed-oak seedling or seedling sprout stems or both in young Piedmont natural hardwoods following clearcut regeneration (winter 1996/1997); Hill and Schenck Forests, NC

Treatment, *P*-value	Seedling species and source									
	GA RO	VA RO	GA WO	VA WO	OS NO	GA RO	VA RO	GA WO	VA WO	OS NO
	3-year height increment					3-year basal diameter increment				
	inches									
Control	4.7	8.7	15.7	9.1	35.0	0.090	0.118	0.228	0.094	0.464
Fertilized	4.7	12.6	16.9	11.8	41.7	0.114	0.134	0.150	0.067	0.681
Weed mat.	10.6	11.0	19.7	11.4	27.6	0.165	0.106	0.193	0.102	0.472
Fert. + mat.	8.7	13.4	18.5	13.0	43.3	0.169	0.113	0.181	0.169	0.776
P-value ≤	0.2	NS	0.1	NS	0.2	0.1	NS	NS	0.05	0.05

GA = Georgia; VA= Virginia; OS = on site; RO = red oak; WO = white oak; NA = natural oaks; NS = not significant.

and to lessen the impact of self-thinning in the subsequent stand (Barnes and Van Lear 1998; Brose and others 1999; Johnson 1993; Kelty 1988; Loftis 1990a, 1990b). Individual tree release of select stems following harvest may facilitate adequate preferred species stocking as well as, or more efficiently than, the advance regeneration approach. Whereas the latter calls for very many oak regenerants per acre prior to overstory removal, the postharvest approach described here, if substantiated, would require only a few hundred (or fewer) stems per acre to ensure adequate representation of oaks in the next harvest.

Results reported here from the enrichment planting study suggest that the species composition of naturally regenerated stands can be enhanced or altered. However, these results are too preliminary to determine if the enrichment-planted trees will thrive and survive through the rotation. This approach may provide a means to not only direct species composition but also to deploy genetically improved individuals (Schlarbaum and others 1997) and thereby create "an individual tree plantation, one tree at a time."

Both the individual tree-release and enrichment-planting approaches may require supplementary treatments at regular intervals to sustain them in the canopy. The likelihood that these approaches could be economically viable (Dutrow 1980), remains unknown. However, recent economic modeling suggests that silvicultural interventions in young natural hardwood stands may be attractive due to productivity enhancements and improved species composition (Siry and others, in press).

ACKNOWLEDGMENTS

We acknowledge the field assistance of Brandon Greco, A. Corbitt Simmons, Mark Romagosa, John Rapp, Karin Hess, Jimmy Dodson, Nathalie Hascoat, and others on the Hardwood Research Cooperative's and College Forest's field crews. This work was supported by the members of the North Carolina State Department of Forestry Hardwood Research Cooperative, and a grant from the Hardwood Forestry Fund.

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FIRST-YEAR RESPONSE OF AN UPLAND HARDWOOD FOREST TO FIVE LEVELS OF OVERSTORY TREE RETENTION

Callie Jo Schweitzer[1]

Abstract—Response of a north Alabama upland oak-hickory forest to five levels of overstory tree retention was compared following treatment. Fifty-acre experimental blocks were established on the mid-Cumberland Plateau, which included the highly dissected margins and sides of the southern subregion. Blocks were replicated three times. Each of the five retention treatments (corresponding to 100-, 75-, 50-, 25-, and 0-percent basal area retention) was randomly assigned within 10-acre units of each block. Leave trees within treatments were marked based on species and crown position, and the harvest was implemented by chain saw felling and grapple skidding. The 75-percent retention treatment was accomplished using stem-injected herbicide, and most injected stems were midstory canopy trees. An average of 381 stems per acre were treated with herbicide, and the average diameter of treated trees was 2.9 inches diameter at breast height. Following treatment, canopy tree basal area was not significantly different between the control and the 75-percent retention treatments, but these two treatments retained significantly greater basal area than the other three. The residual basal area between the 25-percent retention (28 percent retained) and the 50-percent retention (38 percent retained) treatments was not significantly different but did differ significantly from the clearcut, control, and 75-percent retention treatments. The treatments created a gradient in light levels and percent canopy cover. One year after harvest, the number of sugar maple and oak seedlings < 1 foot tall has decreased, the number of oak seedlings > 1 foot increased, and yellow-poplar seedlings of all sizes increased.

INTRODUCTION

The oak-hickory forest type dominates forests of northeastern Alabama. In Jackson County, located in the northeastern corner of the State, 79 percent of the 451,000 acres of timberland were classified as oak-hickory (Hartsell and Brown 2002). These forested systems have faced similar stresses as other Southern Appalachian hardwood systems, including a mixed history of indiscriminant logging, fire, and sporadic, severe weather events. Over 50 to 100 years, the result of these large-scale disturbances was a massive intrusion of oaks (*Quercus* spp.), yellow-poplar (*Liriodendron tulipifera* L.), ash (*Fraxinus* spp.), and other important species. Today's upland hardwood forests in the Tennessee Valley of north Alabama and adjacent regions contain a mixture of species with wide ranges of shade tolerance and growth rates. Our research now focuses on how to manage the resulting stand structures and species compositions to meet current utilization goals and achieve our desired future conditions.

Regenerating hardwood stands in similar systems has been documented in key studies by Loftis (1983a, 1983b, 1985, 1990), McGee (1967, 1975, 1979), McGee and Hooper (1970), Sander (1971, 1972), Sander and Clark (1971), and Sander and others (1976). These studies have shown that growth rates of oak reproduction following a harvest are a function of the size of advance reproduction, and that it is important to consider preexisting vegetative structure, including both stump sprouts and advance reproduction.

Shelterwood harvest is an alternative regeneration method that requires a sequence of cuttings over a 5- to 20-year interval and multiple entries into the stand. Where an oak component is favored, this technique has shown promise in regenerating stands. The residual basal area in a shelterwood must be high enough to prevent light-seeded species, in many cases yellow-poplar, from becoming established and growing. Stands that contain species of opposing shade tolerances, such as those in northeastern Alabama, present yet another challenge. The change in canopy structure and below-canopy light conditions may also favor shade-tolerant species such as sugar maple (*Acer saccharum* Marsh.). In addition to overstory reduction, treating the subcanopy may promote the development of desired species.

The main objective of this study was to quantify forest regeneration, by source and species composition, using a range of crown covers and basal areas. The effects of varying the intensity of forest overstory retention on oak reproduction establishment and growth will be followed and light conditions created by these stand manipulations will be used in quantifying the changes among treatments.

METHODS

Study Sites

To assess the shelterwood method of regenerating upland hardwood stands, three sites on the mid-Cumberland Plateau in Jackson County, AL, were chosen. The stands are located on strongly dissected margins and sides of the plateau (the escarpment). On the escarpment study sites, soils are characterized as deep to very deep and loamy. They are considered well drained, with moderate to moderately low soil fertility. Slopes range from 15 to 30 percent. Upland oak site index was 75 to 80, and yellow-poplar site index was 100 [base age 50 years, Smalley Landtype 16, plateau escarpment and upper sandstone slopes and benches—north aspect (Smalley 1982)]. Canopies were dominated by oaks (*Q. velutina* Lamarck, *Q. rubra* L., *Q. alba* L., *Q. prinus* L.), yellow-poplar, hickories (*Carya* spp.),

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

and sugar maple, with a lesser proportion of ash and blackgum (*Nyssa sylvatica* Marsh.). Depending on the site, dogwood (*Cornus florida* L.), sourwood (*Oxydendrum arboreum* DC.), Carolina buckthorn (*Rhamnus caroliniana* Walt.), and eastern redbud (*Cercis canadensis* L.) were common understory species. Beneath mature stands oak reproduction was small and sparse, and competition by yellow-poplar and sugar maple was great.

Each site (block) comprised one replication of five treatments established along the slope contour. One replication, located on Miller Mountain (34°58'30"N., 86°12'30"W.), had a southwestern aspect and a mean elevation of 1,600 feet. Two replications, located at Jack Gap (34°56'30"N., 86°04'00"W.), both had northern aspects. One Jack Gap replication was located at 1,500 feet elevation and the other at 1,200 feet elevation. Treatments were randomly assigned to 10-acre areas within each replicated block. The treatments constituted five levels of overstory basal area retention: (1) 100 percent, untreated control; (2) 75 percent; (3) 50 percent; (4) 25 percent; and (5) 0 percent, clearcut. For the 50- and 25-percent retention, trees were marked to be retained using guidelines outlined by John Hodges, following those of Putnam and others (1960). Trees were chosen on the basis of species, favoring oak, ash, and persimmon (*Diospyros virginiana* L.), and class, favoring preferred and reserve growing stock. All leave trees had dominant or codominant crown positions and exhibited high vigor. Trees were harvested by conventional methods of chain saw felling and grapple skidding along predesignated trails. Roads were "daylighted" and trees harvested from fall 2001 through winter 2002.

For the 75-percent retention treatment, an herbicide (Arsenal®, active ingredient imazapyr) was used to deaden the midstory. Rates of application were within the range recommended by the manufacturer. Watered solutions were made in the laboratory, and then trees received application via waist-level hatchet wounds using a small, handheld sprayer. One incision was made per 3 inches of diameter, and each incision received approximately 0.15 fluid ounces of solution. Herbicide treatments were completed in fall 2001, prior to leaf fall. The goal was to minimize the creation of overstory canopy gaps while removing 25 percent of the basal area in the stand midstory. All injected trees were in lower canopy positions, reducing the creation of canopy gaps.

Prior to treatment, five measurement plots were systematically located in each treatment area. Plot centers were permanently marked with a 2-foot piece of reinforcing steel, and Global Positioning System (GPS) coordinates were recorded. Regeneration was sampled on 0.01-acre circular plots. Seedlings were tallied by species in each regeneration plot by 1-foot height classes, up to 1.5 feet diameter at breast height (d.b.h.), and then by diameter. Using the same plot center, a 0.025-acre plot was established, and all trees 1.6 inches d.b.h. and greater were monumented (distance and azimuth measured and recorded from plot center, each tree tagged with a numbered aluminum tag) and species and d.b.h. recorded. An additional 0.2-acre plot, located concentrically, was established, and all trees 5.6 inches d.b.h. were measured and monumented as described previously.

In mid- to late-summer 2002, all measurement plots were revisited. Regeneration was re-enumerated, and the status of all monumented trees was recorded. Wounds on trees 5.6 inches d.b.h. and greater were measured. A handheld spherical densitometer was used to measure canopy cover at two vertical levels, ground and 4.5 feet, at plot center and at 12 feet in each cardinal direction from plot center. An AccuPAR Linear Par Ceptometer, Model PAR-80, was used to measure photosynthetically active radiation at each plot center and along transects equally dissecting each plot.

All the data analyses were accomplished using the Statistical Analysis System (SAS Institute 1990). Analysis of variance was used to test for differences among treatments, and Duncan's Multiple Range test was used for mean comparisons ($p < 0.05$).

RESULTS

Overstory Composition

The initial basal areas of the canopy trees (5.6 inches and larger d.b.h.) for each treatment are given in table 1. There were no significant differences among treatments for total basal area prior to treatment implementation. Oaks occupied most of the canopy in all pretreatment units, ranging from 41 percent in the 50-percent retention treatment to 51 percent in the 25-percent retention treatment. Across all treatment units, oaks comprised 46 percent of the total basal area, followed by 15 percent hickory, 13 percent sugar maple, and 9 percent yellow-poplar. The number of canopy trees averaged 115 stems per acre; oaks, with an average d.b.h. of 16 inches, averaged 35 stems per acre.

Following treatment, the canopy tree basal area was not significantly different between the control and the 75-percent retention treatment, but these two retained significantly

Table 1—Average basal area (trees 5.6 inches d.b.h. and larger) for five retention treatments (pretreatment and posttreatment) and percent of total basal area retained 1 year posttreatment

Treatment	Pretreatment	Posttreatment	Total basal *area*
percent	- - - - - - - ft^2 *per acre* - - - - - - -		*percent*
100 retained (control)	106.2a	105.9a	99.7
75 retained (herbicide)	117.3a	82.1a	70.0
50 retained	106.3a	40.2b	37.7
25 retained	98.7a	27.3b	27.7
0 retained (clearcut)	109.7a	5.1c	4.7

Letters indicate significant difference among means within columns.

greater basal area than the other three treatments. On one of the measurement plots, a 12-inch d.b.h. sugar maple died, and it accounted for the only change in the control treatment basal area. Most of the herbicide-treated trees removed in the 75-percent retention treatment were in the midstory position. An average of 381 stems per acre was herbicide treated, and the average tree diameter of treated trees was 2.9 inches d.b.h. The basal area of trees 1.5 inches d.b.h. and larger for the 75-percent retention treatment was reduced from 115.9 square feet per acre to 86.1 square feet per acre, meeting the targeted 75-percent retention.

Thirty-eight percent of the canopy tree basal area was retained in the 50-percent retention treatment, and 28 percent was retained in the 25-percent retention treatment. The residual basal area on these treatments was not significantly different, but did differ significantly from the clearcut (5 percent retained), control (100 percent retained), and 75- percent retention (70 percent retained) treatments (table 1).

Because residual trees were chosen based on species, the residual-stand species composition varied from that of the original stands, except for the control treatment. For the –75-percent retention treatment, the proportion by species of the canopy tree basal area changed little. Prior to the herbicide treatment, red oaks were 14 percent and white oaks were 37 percent of the total canopy tree basal area, followed by 14 percent hickory, 14 percent yellow-poplar, and 8 percent sugar maple. One year posttreatment, these proportions were 13 percent for red oaks, 32 percent for white oaks, 14 percent for hickory, 12 percent for yellow-poplar, and 8 percent for sugar maple. For the 50-percent retention treatment, the major species proportions pretreatment were 19 percent red oaks, 27 percent white oaks, 20 percent hickory, 8 percent yellow-poplar, and 14 percent sugar maple. Following treatment (harvesting), the overstory tree basal area was composed of 28 percent red oaks, 36 percent white oaks, 13 percent hickory, 7 percent yellow-poplar, and 8 percent sugar maple. The 25-percent retention treatment species composition demonstrated a pattern similar to the 50-percent retention. Other tree species removed from these stands included red maple (*A. rubrum* L.), sourwood, sassafras (*Sassafras albidum* L.), blackgum, black locust (*Robinia pseudoacacia* L.), and American beech (*Fagus grandifolia* Ehrh.).

Residual Tree Damage

Damage to the residual trees was evaluated for the 25- and 50-percent retention treatments by crown observations and by measuring wounds on the lower bole. Less than 1 percent of the residuals in the 50-percent retention treatment and 6 percent of the residuals in the 25-percent retention treatment suffered any type of noticeable crown damage. Most of the damage was to the boles, and this damage was concentrated on the lower bole area; only one wound was noted 10 feet or higher on any bole. For the 50-percent retention treatment, 25 percent of the residual trees had wounds on the lower bole, and these averaged 131 square inches. The amount of bole damage for the 25-percent retention was 15 percent, and the average wound size was 70 square inches. No immediate response of epicormic branching was noted on the residuals during the first growing season after treatment.

Canopy Cover and Understory Light Conditions

One goal of these stand manipulations was to evaluate vegetation responses under various light levels. Canopy cover percentages and the percent of full sunlight measured 4.5 feet above the ground are given in table 2. Percent canopy cover did not differ significantly between the control and the 75-percent retention treatment, but the amount of light reaching the understory was significantly greater in the 75-percent treatment than the control (table 2). Canopy cover and light levels were similar for the 50- and 25-percent retention treatments, and these differed significantly from the other three treatments. At the end of the first growing season after treatment, a gradient of light was recorded across four treatments, following the basal area reductions.

Regeneration

Across all treatments, large advance reproduction, > 1 foot tall but < 1.5 inches d.b.h., averaged 3,313 stems per acre (table 3). The oak component was low, making up 2 percent (71 stems per acre) of the total large advance reproduction. Small advance reproduction, < 1 foot tall, averaged 6,671 stems per acre, and small oaks were 13 percent of this total. Across all treatments, large advance reproduction was dominated by sugar maple (389 stems per acre) and ash (206 stems per acre).

After the 75-percent retention treatment, total seedling counts and the number of oak seedlings were below pretreatment counts (table 3). There was a slight increase in both small and large advance reproduction of sugar maple.

Table 2—Comparisons among five basal area retention treatments for percent canopy cover at two understory positions; and percent full sunlight measured at 4.5 vertical feet in the understory, 1 year posttreatment

Treatment	Canopy cover at ground level	Canopy cover at 4.5 feet	Full sunlight at 4.5 feet
		percent	
100 retained (control)	100a	100a	8a
75 retained (herbicide)	98a	98a	16b
50 retained	79b	75b	38c
25 retained	79b	76b	32c
0 retained (clearcut)	51c	32c	60d

Letters indicate significant difference among means within columns.

Table 3—Number of stems per acre by size class for select species and total of all species, by basal area retention treatment, for pretreatment (pre) and year 1 posttreatment (post) counts

Size class and species	Treatment retention (percent)									
	100 Control		75 Herbicide		50		25		0 Clearcut	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
	number of stems per acre									
≤1 all	4,982	4,186	7,798	6,573	4,581	6,180	5,342	5,186	10,653	5,453
>1 all	2,615	2,480	2,579	2,586	3,995	3,674	4,075	4,213	3,299	2,960
≤1 oaks	699	780	1,652	1,520	400	480	713	673	746	340
>1 oaks	200	193	40	20	26	46	40	140	47	107
≤1 sugar maple	959	867	1,538	1,593	1,185	687	833	613	1,312	533
>1 sugar maple	147	133	500	553	353	360	366	400	573	373
≤1 yellow-poplar	0	0	73	33	33	820	13	647	13	1,540
>1 yellow-poplar	7	7	20	33	0	160	13	93	20	160
≤1 ash	173	127	212	160	226	707	127	413	539	760
>1 ash	113	87	53	67	433	407	206	260	226	393

< 1 = to 1 foot in height; > 1 = greater than 1 foot tall but less than 1.5 inches d.b.h.

In the clearcut treatment, total oak seedling stems per acre declined for the smallest size class and increased for the largest. The number of oak stems per acre increased in the 50-percent retention treatment, from 400 to 480 stems per acre for small seedlings, and from 26 to 46 stems per acre for large seedlings. Large oaks also increased in the 25-percent retention treatment, from 40 to 140 stems per acre.

In three harvest treatments (25- and 50-percent retention and clearcut), both large and small advance sugar maple reproduction declined in numbers, from an average of 1,110 stems per acre to 611 stems per acre for the smallest sugar maple seedlings, and from 431 stems per acre to 378 stems per acre for the largest. For both size classes, the number of stems per acre of yellow-poplar increased in all three of these treatments. The number of ash seedlings per acre also increased, except for large advance ash in the 50-percent retention treatment, which declined slightly.

In the clearcut, prior to treatment, sugar maple and red maple accounted for 12 and 48 percent of the total seedling count in the small reproduction class, and yellow-poplar was < 1 percent (13 stems per acre). Posttreatment small sugar maple and red maple seedlings comprised 10 and 2 percent of the total stems per acre, respectively, and yellow-poplar increased to 28 percent (1,540 stems per acre). This trend was similar for both the 50- and 25-percent retention treatments.

DISCUSSION

Upland hardwood forests on escarpment sites in north Alabama have unique species composition. Site quality is good, and the dominant species include white and red oaks, ash, yellow-poplar, hickory, red maple, and sugar maple. The range of shade tolerance exhibited by these species contributes to the challenge of regenerating timber stands. Oaks, which had low advance reproduction numbers, and which were small in stature, are key species in the stand's desired future condition. The challenge of this study was to manipulate the stand to foster the growth and development of small oaks, while simultaneously discouraging the proliferation of yellow-poplar. Under the varying canopy cover and light levels, the response of the small but numerous sugar maple seedlings on these sites was uncertain.

The gradient in overstory canopy cover and understory light levels was accomplished by removing varying amounts of the overstory and midstory basal area. By selecting leave trees prior to harvest, the residual stand composition in the 25- and 50-percent retention treatments was changed. High-value species were favored. After one growing season, a few trends in the regeneration response were noted.

The increase in yellow-poplar seedlings following harvesting (25- and 50-percent retention treatments and clearcut) supports the findings of others (Kuers and Kuthe 1998, Loftis 1983b, McGee and Hooper 1970). An increase in early successional species was measured on all harvested areas. The contribution of stem sprouts to the reproduction in these treatments will influence the stands' future composition. Modeling of sprouting potential will aid in evaluating the contribution of stem sprouts to the new stand, and the competitiveness of oak and other species. The growth rate of early successional species (yellow-poplar, black cherry, black locust, red maple) coupled with sprouting competition potentially will influence the future eminence of oak.

Golden and others (1999) assessed oak regeneration in a north Alabama stand following clearcutting and a deferment cut that retained approximately 25 percent of the original basal area. They found the most influential factor related to postharvest stocking of oak was the presence of advance reproduction taller than 6 inches, contrasting with others' findings (Loftis 1983a, 1983b, 1990; Sander 1971, 1972). One goal of establishing a gradient of basal area retentions

and light levels was to determine what degree of harvest would allow adequate development of advance oak regeneration, based on the size-class status of reproduction present.

Shelterwood cutting successfully altered stand structure and species composition. Stand density was reduced and species composition altered to promote the growth and development of residual trees. Growth and vigor of a residual stand will help meet future timber and wildlife needs, as well as contribute to the next age class through sprouting. Logging damage to residual stems was confined to lower boles and occurred on 15 to 25 percent of residual stems > 5.6 inches d.b.h. These values were considerably lower than those reported by Meadows (1993) in a bottomland hardwood stand (62 percent residual damage) and fell within the range of 18 to 42 percent residual damage reported by Lamson and others (1984) in an upland hardwood stand. Directional felling and preplanned roads and skid trails contributed to mitigating unnecessary residual damage. Wounds to residual trees and epicormic branching will be monitored.

CONCLUSIONS

A large-scale stand manipulation study was implemented, resulting in four treatments that had significantly different residual basal areas. Prior to harvest, advance reproduction was dominated by sugar and red maples, and there were few oaks. Since the harvests, small (< 1 foot in height) sugar maple and oak seedling numbers have declined, and there have been more large oak seedlings. However, competition is increasing with the pervasion of yellow-poplar seedlings. Reduction of the midstory altered light levels on the ground differently than the other harvest treatments. The response of both the advance oak reproduction and the more shade-tolerant sugar maple seedlings will be monitored closely under these treatments.

ACKNOWLEDGMENTS

This research was made possible through the generous support of MeadWestvaco, Stevenson, AL. Special gratitude goes to Greg Janzen, Greg McCord, Charles Bowen, Callie Dixon, Ryan Sisk, Jenny Mainor, Cameron Isbell, Cory Gillespie, and Scott Helms, as well as to the staff of Bent Creek Experimental Forest.

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INDIVIDUAL OAK TREE GROWTH IN SOUTHERN BOTTOMLAND HARDWOOD STANDS (PRELIMINARY RESULTS)

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Abstract—Southern bottomland hardwood forests are an important natural resource. Silvicultural practices in them are often intended to provide suitable growing conditions to selected individual trees of valuable species by employing crop-tree management. Research on crop-tree management, however, has been considerably less than the research regarding stand-level management. In this study, trees from three bottomland hardwood sites were measured to perform regression analysis on d.b.h. growth and basal area growth of selected red oak group trees. The new variable score for direct sunlight from above and from the sides accounted for more variability in the growth models than other variables and indices from the literature. The new crown-class score is visually determined and requires only a simple calculation, which should make it useful for practitioners and researchers interested in predicting the growth of individual trees from the red oak group.

INTRODUCTION

Southern bottomland hardwood stands commonly occupy productive sites on major and minor stream bottoms (Hodges 1995). These forests are often naturally regenerated and characterized by a complex vertical structure combined with a diverse species composition. Their structural complexity and the presence of intricate interspecific and intraspecific relationships make research challenging. Therefore, to describe them quantitatively, very detailed data collection is needed. Necessary information includes individual tree dimensions and their spatial distribution.

Determining competition among trees is of considerable research interest, in part because competition is a common component of tree-growth models. Competition is assessed through variables describing the characteristics of neighboring trees or through competition indices, which are combinations of these variables. Independent variables used in the literature include crown-based variables (Cole and Lorimer 1994, Moore and others 1973, O'Neal and others 1994) and diameter-based variables (Faber 1991). In these and in other studies (Biging and Dobbertin 1992, Daniels and others 1986, Tome and Burkhart 1989), the two types of variables accounted for various amounts of the variability in d.b.h. and basal area growth, but neither of the two types of variables performed consistently better. Competition indices are usually divided into distance-dependent indices, when the intertree distances are taken into consideration, and distance-independent indices when the intertree distances are not taken into account (Munro 1974).

In this study, cherrybark oak (*Quercus pagoda* Raf.) was the species of main interest, although red oaks in general were also of consideration. Cherrybark oak was selected for its superior growth, economic value, and importance in the southern bottomland ecosystems (Burns and Honkala 1990). The objectives of this project were to find the factors that can best explain the variability in d.b.h. and basal area growth of selected trees by considering the characteristics of the individual trees and the other plot trees.

METHODS

Three 0.64-ha plots were established on each of three bottomland hardwood sites. One of the sites was on a major stream bottom (Mississippi River) and is located in St. Landry Parish, central Louisiana. The remaining two sites are on minor stream bottoms. One was located in Jackson Parish (Cypress Creek) in northern Louisiana and one in Drew County (Hungerrun Creek) in southeastern Arkansas. The stands were naturally regenerated, mature (more than 70 years old), relatively undisturbed (no cutting in approximately the previous 20 years) and dominated by red oaks. The soils on the St. Landry Parish site are Baldwin silty clay loam (fine montmorillonitic, thermic Vertic Epiaquals); on the Jackson Parish site, the soils are Guyton silt loam (fine-silty, siliceous, thermic Typic Glossaqualfs); and on the Drew County site, the soils are Ouacuta silt loam (fine-silty, siliceous, thermic Fluventic Dystrochrepts).

A dominant or codominant cherrybark oak that would be chosen as a crop tree during thinning was used for the central tree of each plot. For this study, a crop tree was considered a cherrybark oak tree that satisfied the objective of growing high-quality sawtimber. The spatial locations of all trees larger than 10.0 cm in diameter at breast height (d.b.h.) were recorded. Instruments used to map the tree locations included a ForestPro laser hypsometer-rangefinder, and a MapStar Angle Encoder (LaserTech, Inc.). Each tree's d.b.h. was measured and the species and crown class determined. Additional measurements collected for the overstory trees (dominant, codominant, and intermediate crown classes) included total height, height to the base of the crown, and vertically projected crown radius in each of the four cardinal directions. Tree heights were measured with the ForestPro, and the vertical projection of the crown edge was determined using a GRS Densitometer, whenever possible, to ensure vertical viewing. Additional data collected for the central crop tree and the two trees considered to be its main competitors included the vertically projected crown radius in four additional directions (total of eight directions). The two

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

main competitors were determined by assessing crown proximity and overlap and the relative tree heights. Crown-class score as defined by Meadows and others (2001), was also determined for the central tree and the two competitors. This crown class numerical rating system assigns ratings for four criteria: (1) direct sunlight from above — values from 0 to 10; (2) direct sunlight from the sides — values from 0 to 10; only the upper half of the crown length was used for this criterion; (3) crown balance — values 1 to 4 were assigned according to the number of quadrants occupied by 20 percent or more of the total crown volume; and (4) relative crown size — values 1 to 4 were assigned for appropriate crown size and density as related to a tree of that diameter and species; one point was assigned if crown size and density were severely limiting to growth, two points if limiting to growth, three points if somewhat limiting to growth, and four points if not limiting to growth.

The point values for the criteria were summed, and crown class was assigned in the following manner: 24-28 points = dominant, 17-23 points = codominant, 10-16 points = intermediate, and 2-9 points = suppressed.

Following the measurements, the crop tree and the two trees considered to be its main competitors were cut. Cross-sections were obtained from 1.37 m (breast height) above the ground. The disks were sanded, and the radial growth for the previous 5 full years was measured in the four cardinal directions. This was not done for competitors that were not from the red oak group. The total number of red oak group trees cut from all 9 plots was 16 cherrybark oaks, 7 water oaks (*Q. nigra* L.), and 1 Nuttall oak (*Q. nuttallii* Palmer).

In this paper, the predicted variables are referred to as dependent variables, and the predictor variables (regressors) are referred to as independent variables. Three dependent variables were measured or calculated from the harvested trees: (1) 5-year d.b.h. growth, (2) 5-year basal area growth, and (3) percent basal area growth (ratio between the 5-year basal area growth and the basal area of the tree 5 years prior to cutting).

The independent variables considered in the analysis included: (1) d.b.h. of the tree 5 years prior to cutting, (2) basal area of the tree 5 years prior to cutting, (3) crown-class score (after Meadows and others 2001), (4) score for direct sunlight from above and from the sides (after Meadows and others 2001), (5) basal area of all plot trees, (6) basal area of all plot trees except the suppressed, (7) basal area of all oak trees on the plot, (8) basal area of all oak trees on the plot except the suppressed, (9) mean crown diameter of the overstory trees, (10) projected crown area, and (11) ratio between the projected crown area and the basal area of the tree 5 years prior to cutting.

The initial regression analysis included simple linear regression analysis. Each dependent variable was regressed against each of the independent variables to assess which independent variable accounted for the most variability in the dependent variable. This was followed by multiple linear regression analysis, where each of the three dependent variables was regressed against all independent variables. The selection of the independent variables to remain in the model was performed by the stepwise selection procedure (SAS 1991). The procedure required the variables to be included in the model if their significance level was less than 0.05 and to be excluded if their significance was over 0.10 after the inclusion of a new variable.

RESULTS

Among the simple linear regression models that used diameter growth as the dependent variable, there were three models whose independent variables were significant at the 0.05 level (table 1). Those three models included one of the following independent variables: score for direct sunlight from above and from the sides, crown-class score, and tree d.b.h. 5 years prior to cutting. The independent variables in the first two models accounted for 55 and 54 percent of the variability in the model, respectively, whereas the last model accounted for only 22 percent. The variability in the models was better accounted for by the crown-based variables than by the d.b.h.-based variable.

Table 1—Simple linear regression models for the three dependent variables. Shown are the independent variables significant at the 0.05 level

Dependent variable	Independent variable	r^2	*P*-value
5-year d.b.h. growth	Score for direct sunlight from above and from the sides[a]	0.55	< 0.001
	Crown-class score[a]	0.54	< 0.001
	D.b.h. of the tree 5 years prior to cutting	0.22	0.022
5-year basal area growth	Basal area of the tree 5 years prior to cutting	0.63	< 0.001
	D.b.h. of the tree 5 years prior to cutting	0.62	< 0.001
	Projected crown area	0.44	< 0.001
	Crown-class score[a]	0.39	0.001
	Score for direct sunlight from above and from the sides[a]	0.39	0.001
	Mean crown diameter of the overstory trees	0.36	0.002
	Basal area of all plot trees except the suppressed	0.27	0.010
Percent basal area growth	Score for direct sunlight from above and from the sides[a]	0.32	0.004
	Crown-class score[a]	0.30	0.006

[a] For definitions of score for direct sunlight from above and from the sides and crown-class score, see the crown-class system by Meadows and others (2001) in the Methods section.

For the simple linear regression models with five-year basal area growth as the dependent variable, there were more models with significant independent variables at the 0.05 level. Each of these models included one of the seven variables: basal area of the tree 5 years prior to cutting, d.b.h. of the tree 5 years prior to cutting, projected crown area, crown-class score, score for direct sunlight from above and from the sides, mean crown diameter of the overstory trees, and basal area of all plot trees except the suppressed (table 1). In general, these variables accounted for a larger amount of the variability in the models compared to the previous case, where the dependent variable was the 5-year d.b.h. growth. The variables basal area of the tree 5 years prior to cutting and d.b.h. of the tree five years prior to cutting had r^2 values of 0.63 and 0.62, respectively. The projected crown area had an r^2 of 0.44, and the latter four variables had r^2 of 0.39, 0.39, 0.36, and 0.27, respectively.

When percent basal area growth was the dependent variable, there were two highly significant variables - score for direct sunlight from above and from the sides, and crown-class score (table 1). However, all variables accounted for only a small part of the variability in the model – 32 and 30 percent, respectively.

Multiple linear regression analysis was then performed on the same three dependent variables; results are presented in table 2. The standardized coefficients demonstrate the relative importance of each variable for the model. For example, for the first dependent variable, the standardized coefficient of 0.73 for the variable score for direct sunlight from above and the sides means that: a one-standard deviation change in the independent variable will lead to a 0.73-standard deviation change in the dependent variable. Thus, it is clear that in this case, the particular variable is more "important" for the model than the second variable—basal area of all oak plot trees except the suppressed, whose standardized coefficient is only 0.29. For the model for 5-year basal area growth, the standardized coefficients differ less from each other. This indicates that the two selected independent variables contribute similarly to the model. In the third multiple linear regression model, where the percent basal area growth is the dependent variable, the standardized coefficients suggest that the variable score for direct sunlight from above and from the sides is more "important" for the model than the mean crown diameter of the overstory trees and basal area of all plot trees.

DISCUSSION

Five-year basal area growth was the factor with the most variability accounted for by the individual independent variables assessed (table 1). When multiple linear regression was performed, the 5-year basal area growth was again the dependent variable with the most variance accounted for (table 2). Unlike the simple linear regression models, the multiple linear regression model for the percent basal area growth accounted for slightly more variation than the model for 5-year d.b.h. growth. The variables crown-class score and score for direct sunlight from above and from the sides appeared to be significant in the simple linear models for all three dependent variables. Additionally, the score for direct sunlight from above and from the sides was selected by the stepwise selection method in each of the three multiple linear regression models. Moreover, the standardized coefficients suggested that this crown-based variable was substantially more "important" than the other

Table 2—Multiple linear regression models for tree growth[a]

Dependent variable and R^2	Independent variable	Unstandardized coefficient	Standardized coefficient	*P*-value
Model 1 5-year d.b.h. growth $R^2 = 0.63$	Intercept	-13.49	—	0.052
	Score for direct sunlight from above and from the sides[b]	1.89	0.73	< 0.001
	Basal area of all oak plot trees except the suppressed	0.46	0.29	0.038
Model 2 5-year basal area growth $R^2 = 0.78$	Intercept	-133.60	—	0.013
	Basal area of the tree 5 years prior to cutting	0.08	0.66	< 0.001
	Score for direct sunlight from above and from the sides[b]	11.71	0.40	0.001
Model 3 Percent basal area growth $R^2 = 0.77$	Intercept	15.35	—	0.004
	Score for direct sunlight from above and from the sides[b]	1.01	0.86	< 0.001
	Mean crown diameter of the overstory trees	-0.01	-0.50	0.001
	Basal area of all plot trees	-0.48	-0.36	0.008

[a] The independent variables were selected by the stepwise procedure (SAS 1991).

[b] For definitions of score for direct sunlight from above and from the sides and crown-class score, see the crown-class system by Meadows and others (2001) in the Methods section.

predictor variables in the models with 5-year d.b.h. growth and percent basal area growth and almost as "important" in the basal area growth model (table 2). Therefore, it appears that the amount of direct sunlight from above and the direct sunlight reaching the upper 50 percent of the crown accounted for most of the variability in diameter and basal area growth. The inclusion of the crown characteristics balance and relative crown size in the crown-class score did not provide a better fit. It is possible that the first two criteria of the crown-class system by Meadows and others (2001) have the most impact on the growth in diameter and basal area. However, thinning may alter these relationships and the growth of other trees remaining after a thinning operation.

Although this study does not have the same design as studies by O'Neal and others (1994) and Cole and Lorimer (1994), some comparisons can be made. This study's multiple regression model for diameter growth accounted for a larger amount of the variability than the model of O'Neal and others (1994): an R^2 of 0.63 for this study's species from the red oak group versus O'Neal and others' (1994) 0.30 and 0.39 for white oak (*Quercus alba* L.) and southern red oak (*Quercus falcate* Michx.), respectively. A new crown-based variable, crown position index (CPI), was tested by O'Neal and others (1994). This variable was based on the relative crown position and crown size as expressed by crown projections and relative heights of the crop trees and their competitors and was calculated by a formula. Calculating the index required the collection of numerous measurements on the crop tree and the competitors. In contrast, determining the score for the criteria direct sunlight from above and from the sides from the rating system by Meadows and others (2001) does not require direct measurements and is easily determined visually. Moreover, as seen by the coefficients of determination above, it appeared to have a higher correlation to the d.b.h. growth than the CPI.

The results for basal area growth models were similar to those of Cole and Lorimer (1994). This study achieved R^2 of 0.78, whereas the models of Cole and Lorimer (1994), who worked with sugar maple (*Acer saccharum* Marsh.), white ash (*Fraxinus americana* L.), and basswood (*Tilia americana* L.), accounted for 0.79, 0.88, and 0.81 of the variability, respectively. They also found the percent-exposed crown area (ECA) to be a variable of specific interest, so it was included in the basal area growth models for all three tree species they worked with. The authors indicated that percent ECA can be used as a crown competition variable to estimate the competitive effects without direct measurement of any of the competitors, which would save field measurement time. However, some measurements on the crop tree are still necessary. Unlike the procedure for measuring and calculating the percent ECA, the procedure for determining the score for direct sunlight from above and from the sides requires neither measurements on any tree, including the crop tree itself, nor calculations (other than a simple summation of two numbers between 0 and 10), which should make it more appealing for use by practitioners in the field. In addition, all variables in the basal area growth models in the study by Cole and Lorimer (1994) are log-transformed. The interpretation for the basal area growth model in this study is straightforward; the results from table 2 clearly indicate that a one-point increase in the score for direct sunlight from above and from the sides will correspond to an 11.71 cm^2 increase in the basal area growth of the tree over the following 5-year period. Nevertheless, some transformation of the model variables in this study and the addition of more data may further improve the performance of the models. The comparisons indicate that the performance of the models in this study is comparable to others reported in the literature

ACKNOWLEDGMENTS

Partial funding for this project was provided by the McIntire-Stennis Cooperative Forestry Act. We would like to thank our reviewers Quang Cao, Steve Meadows, and Jun Xu. We also are appreciative of Resource Management Service, Inc., Willamette Industries, Inc., and the Thistlethwaite Family for making their properties available for the study. We thank Jim Scarborough, Jacob Floyd, Joy Young, Erika Stelzer, Andrew Gross, Kangsheng Wu, and Alexander Michalek for their assistance in data collection. Approved for publication by the LSU AgCenter as manuscript number 03-40-1238.

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Longleaf Pine

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RESTORING UPLAND FORESTS TO LONGLEAF PINE: INITIAL EFFECTS ON FUEL LOAD, FIRE DANGER, FOREST VEGETATION, AND BEETLE POPULATIONS

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Abstract—Without fire in the Southeastern United States, loblolly pine (*Pinus taeda* L.) often becomes the overstory dominant on sites historically dominated by longleaf pine (*P. palustris* Mill.). Beneath the loblolly pine canopy a mature midstory and understory develops of woody vegetation supporting draped fuels. The resulting deep shade and accumulation of litter nearly eliminates herbaceous vegetation. To avoid this outcome, on most upland sites a series of treatments can ensure the restoration of longleaf pine plant communities and lessen the danger of wildfires. Burning in heavy fuels, however, may injure and weaken pine trees, favoring detrimental insects, such as bark beetles. This Joint Fire Science Program project was established to study how several management options affect fuel load, fire danger, vegetation, and beetle populations in loblolly pine, mixed pine, and longleaf pine stands. We report first and second growing-season results.

INTRODUCTION

In the Southeastern United States, forest fuels accumulate, and without fire management, understory vegetation can shift from grasses to woody plants with significant numbers of highly flammable shrubs supporting draped fuels (Haywood and Grelen 2000, Haywood and others 2001). We believe this shift in vegetation increases fire intensity, which makes fire fighting more hazardous and costly and places property and natural resources in greater danger. To lessen risk, many forest managers are trying to increase the use of fire and species-specific thinning in upland forest landscapes. Their goal is to ultimately restore existing upland hardwood and loblolly pine (*Pinus taeda* L.) forests to native fire-dependent longleaf pine (*P. palustris* Mill.). The desired future condition is pure longleaf overstories [where 80 percent or more of the basal area is longleaf pine (Helms 1998)], with few hardwoods except in riparian and other moist areas, and a rich and diverse ground cover of herbaceous and low woody plants.

There are problems with using fire. Fire can adversely affect both individual longleaf pine trees and stand health (Boyer 1987, Boyer and Miller 1994). For us, a prime concern is a reduced resistance to bark beetles in fire-stressed stands. In particular, southern pine beetle (*Dendroctonus frontalis*) and Ips engraver beetle (*Ips* spp.) are the most destructive group of insects in the pine forests of the Southern United States. Additionally, ambrosia beetles (*Platypoididae*) are often attracted to fire-stressed stands and are vectors of known and suspected root pathogens. Longleaf pines tolerate fire and have high resin flow rates that make them more resistant to bark beetle attack than other southern pines. Still, the effects of fire on the interaction of insect pests and longleaf pine health are largely unknown. This lack of knowledge is a major concern given the high fuel loads and mixed composition of many upland stands currently undergoing fire-aided restoration efforts. Once the desired future condition is achieved, we expect that frequently applied low-intensity fire will not be as damaging as fires in stands laden with heavier fuels.

The effects of a single prescribed burn are often transitory, and a series of burns over many years must be completed to have lasting changes in plant communities (Olson and Platt 1995). Thus, mechanical methods may be required where managers must restore certain plant communities quickly. Mechanical brush control may also be needed where midstory vegetation is too large to control with burning (Haywood and Harris 1999, Haywood and others 2001). In this Joint Fire Science Program project, we evaluate the outcome of several management schemes involving fire and mechanical treatment in upland loblolly pine forests being restored to longleaf pine in the west Gulf Coastal Plain. We consider changing fuel conditions, fire danger, vegetative composition, and beetle populations.

CLIMATE AND FOREST HISTORY

Our sites lie within the humid, temperate, Coastal Plain, and flatwoods province of the west gulf region of the Southeastern United States. We study loamy dry-mesic uplands where longleaf pine forests once dominated (Turner and others 1999). They are located within the boundaries of the Kisatchie National Forest in central Louisiana at an average elevation of 30 to 60 m above sea level. Slopes vary from 1 to 10 percent. The area's climate is subtropical; mean temperatures in January are 8 °C and in July are 28 °C. Annual precipitation averages 1525 mm with > 965 mm during the 250-day growing season, from March 10 to November 15 (the spring and fall dates with a 50-percent probability of a frost) (Louisiana Office of State Climatology 2001).

The original longleaf pine forests were cut beginning in the 1920s. Although some small stands of longleaf pine remained, most of the area vegetation consisted of perennial grasses under scattered pines and hardwoods maintained by periodic burning for open-range grazing. In the 1950s managers excluded hogs and regulated cattle grazing. Eventually, natural and planted stands of hardwoods and pines reforested much of the landscape.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

METHODS

We established four demonstration sites in this landscape that represent stages in the change from loblolly pine to longleaf pine: a loblolly pine stand, two mixed pine stands, and a seedling and sapling longleaf pine plantation. Each of the demonstration sites is about 8 ha. We divided each into three parts and randomly assigned three treatments: (1) check—no treatment, (2) biennial prescribed burning beginning in May 2001, and (3) biennial prescribed burning and mechanical woody plant control (MWPC) in July 2002. In treatment 3, MWPC plots were prescribed burned as in treatment 2, and the understory vegetation was cut to within 5 cm of the ground with a machine-mounted horizontal-shaft drum shredder (Woodgator®). Due to dry soil conditions in May 2001, a burning root breached the fireline at the loblolly pine site, and a portion of the check treatment area was accidentally burned.

Plot Layout and Measurement

A 0.10-ha main plot was established within each of the treatment areas. In April 2001, woody plants > 10-cm diameter at breast height (d.b.h.) (height of stem 1.4 m above groundline) were measured and inventoried by species. The overstory and midstory vegetation was again examined in July 2001, 6 weeks after the burns. Trees and shrubs 2.5 to 10 cm d.b.h. were measured on four 10-m^2 subplots, randomly selected and permanently established within each main plot. Eight understory vegetation classes comprise trees and shrubs < 2.5 cm d.b.h.: blackberry, woody vines, ferns, forbs, grasses, grasslikes, and legumes. Cover for each class was estimated to the nearest percent on a 1-m^2 subplot nested within each 10-m^2 subplot.

To determine changes in available fuels, four 2- by 5-m fuel subplots were randomly selected and permanently established within each main plot. Each fuel subplot was divided into ten 1-m^2 subplots for sampling without replacement. Fuel samples were collected on one subplot per fuel subplot a month before the May 2001 prescribed burns. A second subplot was sampled 6 weeks after the burns. Fuel samples were divided into five classes considered available for combustion based on Deeming and others' (1977) fire danger rating system: (1) living foliage of all trees, shrubs, vines, grasses, and forbs within 2 m of the ground; (2) living blackberry canes, woody stems, and vines < 6-mm in diameter within 2 m of the ground; (3) 1-hour time-lag dead fuels [surface litter and duff (0- to 6-mm in depth) and roundwood and stubble < 6-mm in diameter]; (4) 10-hour time-lag dead fuels (litter from 6- to 25-mm in depth and roundwood and stubble between 6- and 25-mm in diameter); and (5) 100-hour time-lag dead fuels (litter from 25- to 100-mm in depth and roundwood between 26- and 75-mm in diameter). The sampled fuels were ovendried and weighed.

Beetles were collected over the whole 8-ha treatment area; thus an unburned check was available at the loblolly pine site. Beetle responses to fire were investigated using both flight interception and pitfall traps, with both ethyl alcohol and turpentine as attractants. Ten traps were placed within each of the three treatments per demonstration site. Trapping was conducted 3 to 4 weeks pretreatment and 6 to 8 weeks posttreatment. Beetles were collected and counted weekly, and the number of beetles collected was compared to determine if a significant change in beetle abundance occurred due to treatment. Additionally, trees were monitored at periodic intervals throughout the study to determine rates of beetle attack and subsequent decline in health.

Data Analysis

For burned vs. unburned treatments, fuel loads were compared using a completely randomized analysis of variance (ANOVA) model ($\alpha = 0.05$) (Steel and Torrie 1980). Using covariate analyses did not change interpretation of results. The fuel-load values were the natural log transformation of the ovendried weight (kg/ha) of either the living or dead fuels. Live fuels are foliage, small living stems, and regrowth 6 weeks after burning; dead fuels are 1-hour, 10-hour, and 100-hour time-lag fuels and needle cast 6 weeks after burning. For each forest type (loblolly pine, mixed pine, or longleaf pine plantation), percent cover of the eight understory vegetation classes was also compared between the burned vs. unburned treatments. The percentage data was arcsine transformed before analysis using a two-factor ANOVA.

Three guilds, or groups, of beetles were used in the analyses: ambrosia beetles, bark beetles (*Hylastes tenuis* and *salebrosus, I. grandicollis* and *arulsus,* and *D. terebrans*), and weevils (*Cossonus corticola*, *Hylobius pales*, and *Pachylobius picivorus*). The southern pine beetle was not collected during 2001 and 2002. By guild and in toto, beetle numbers were compared by site and treatment for the prescribed burns in 2001 and the MWPC treatments in 2002 using SAS Mixed Procedure analysis ($\alpha = 0.05$) (Littell and others 2002). The sites included in these analyses were the loblolly pine and mixed pine stands.

RESULTS AND DISCUSSION

Fuel Loads and Fire Danger

For the May 2001 burns, fire intensity was 550 kJ/second/m in the loblolly pine, 1391 kJ/second/m in the mixed pine, and 467 kJ/second/m in the longleaf pine plantation stands. These burns were three to eight times more intense than the 173 kJ/second/m intensity recommended by Deeming and others (1977) as a maximum for prescribed burns.

The average preburn weight of the living available fuels (foliage and stems) was similar across all sites and averaged 1548 kg/ha. Fire greatly affected these two fuel classes. At the loblolly pine, mixed pine, and young longleaf pine plantation sites, ovendried weight of foliage was reduced by 89, 96, and 63 percent, respectively; ovendried weight of stems was reduced by 95, 99, and 95 percent, respectively (fig. 1). However, within 6 weeks postburn, regrowth replaced 17, 12, and 58 percent of the preburn living fuels on the three sites, respectively. Needle cast from the burns occurred at all sites, but most significantly at the mixed pine sites where the fire intensity was greatest. The weight of 1-hour time-lag dead fuels was reduced by 62 percent across all sites. Overall, burning reduced total available fuel load from an average of 9198 kg/ha to 4124 kg/ha, but needle cast and regrowth replaced 1015 kg/ha of available fuel by 6 weeks after the burns. Still, the burns greatly reduced the fire danger by removing over half of the available fuels.

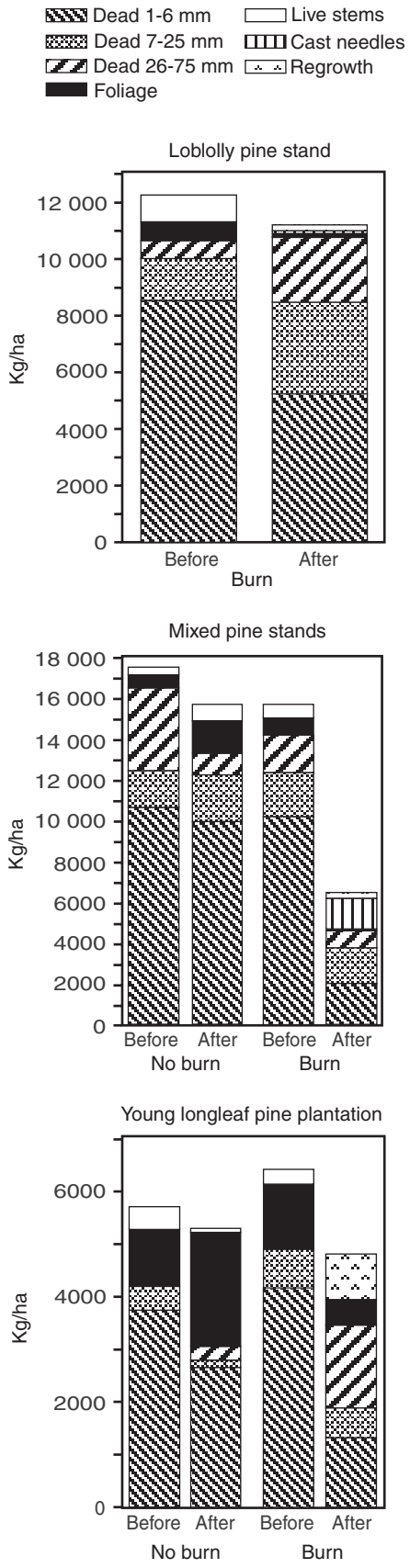

Figure 1—Changes in fuel classes (kg/ha ovendried weight) on the unburned and burned portion of each forest type. Fuel classes were sampled 1 month before the May 2001 burns and 6 weeks after burning.

Vegetation

Prescribed burning did not affect the overstory and midstory vegetation. The loblolly pine site consisted of several tree species in the canopy, but > 80 percent of the basal area was loblolly pine (table 1). The mixed pine sites were also predominately loblolly pine, but loblolly pine was not dominant in the midstory. Longleaf pine was the only

Table 1—Characteristics of the three forest types[a]

Stand type, canopy position	D.b.h.	Basal area
	inches	*ft² per acre*
Loblolly pine		
Overstory		
Pinus taeda	13.4	83 (81%)[b]
P. palustris	16.5	7 (7%)
Liquidambar styraciflua	6.7	4
Prunus serotina	10.3	3
Cornus florida	5.5	3
Nyssa sylvatica	6.2	2
Midstory		
Pinus taeda	3.8	0.23
L. styraciflua	1.0	0.01
Carya tomentosa	1.8	0.03
Mixed pine		
Overstory		
Unburned stand		
Pinus taeda	17.5	72 (72%)
P. palustris	15.7	18 (18%)
Quercus falcata	14.3	6
Q. marilandica	4.8	1
Prunus serotina	10.0	1
Nyssa sylvatica	8.5	1
Burned stand		
Pinus taeda	15.4	79 (81%)
P. palustris	13.1	15 (15%)
Q. falcata	5.2	< 1
Q. marilandica	5.3	2
Q. stellata	5.3	1
L. styraciflua	6.5	< 1
Midstory		
Unburned		
Q. falcata	2.0	0.05
Burned		
Q. marilandica	3.1	0.12
Longleaf pine plantation		
Overstory		
Unburned stand		
P. palustris	4.2	6.0
Burned stand		
P. palustris	4.1	7.7
Midstory		
Unburned stand		
P. palustris	2.6	0.7
Burned stand		
P. palustris	2.9	0.6

[a] Overstory and midstory vegetation was unaffected by burning.

[b] By stand type, percent of the total basal area in the overstory.

species in the overstory and midstory of the longleaf pine plantation.

After the burn at the loblolly pine site, remaining understory trees, shrubs, blackberry, and woody vines shaded 42 percent of the ground (fig. 2). At the mixed pine sites, burning reduced understory tree, shrub, blackberry, and vine cover by 74 percent, but the coverage of forbs and ferns increased after burning. Rapid recovery of forbs and ferns normally follows prescribed burning. In the seedling and sapling longleaf pine plantation, grasses dominated the understory vegetation, and burning had little effect on the relative importance of the plant taxa. The burn reduced overall ground cover from 97 to 85 percent in the longleaf pine plantation.

Beetles

After the May 2001 burns, there were significantly fewer ambrosia beetles collected than either bark beetles or weevils overall (fig. 3). The burned loblolly pine site had greater numbers of collected beetles than all other sites, and 76 percent of the beetles collected at the loblolly pine site were weevils. The majority of the weevils were *C. corticola*, which is an associate of the southern pine beetle (Goyer and others 1980). In general, more bark beetles and weevils were captured in burned stands than in check stands, but these differences were not significant. Too few ambrosia beetles were collected to determine response trends.

After MWPC in July 2002, one of the mixed pine sites had significantly more beetles captured than the other two sites (fig. 3). Only the number of weevils significantly differed among sites or between check and MWPC treatments.

MANAGEMENT IMPLICATIONS

We concluded that a single burn did not greatly change overall fuel conditions or the composition of the understory vegetation, but single burns rarely do (Olson and Platt 1995). Still, our burns initially reduced available fuel load by 55 percent, and this reduction temporarily lowered the risk of catastrophic wildfire destroying natural resources and property or endangering lives.

The beetles we found not only directly attack pine trees but may be vectors of pathogenic fungi (Goyer and others 1980). Burning increased bark beetle and weevil activity on all sites (fig. 3). Although statistically insignificant, these results suggest that if bark beetles are active, particularly the southern pine beetle, burning should be postponed in overstocked stands. Burning is also ill-advised where fuel loads are high and significant crown scorch and charring are expected. Of particular concern would be fires that move too slowly through abundant fuels at the base of trees, resulting in basal scarring, cambial death, and root damage. MWPC did not generally affect the abundance of beetles on these pine sites.

We expect that additional burning with or without MWPC will not greatly change the overstory vegetation. However, we believe a conscientious management plan implementing both fire and MWPC in stands should eventually create a grass-dominated fuel bed that favors low-intensity rapid fires and thereby reduces tree injury and beetle attack.

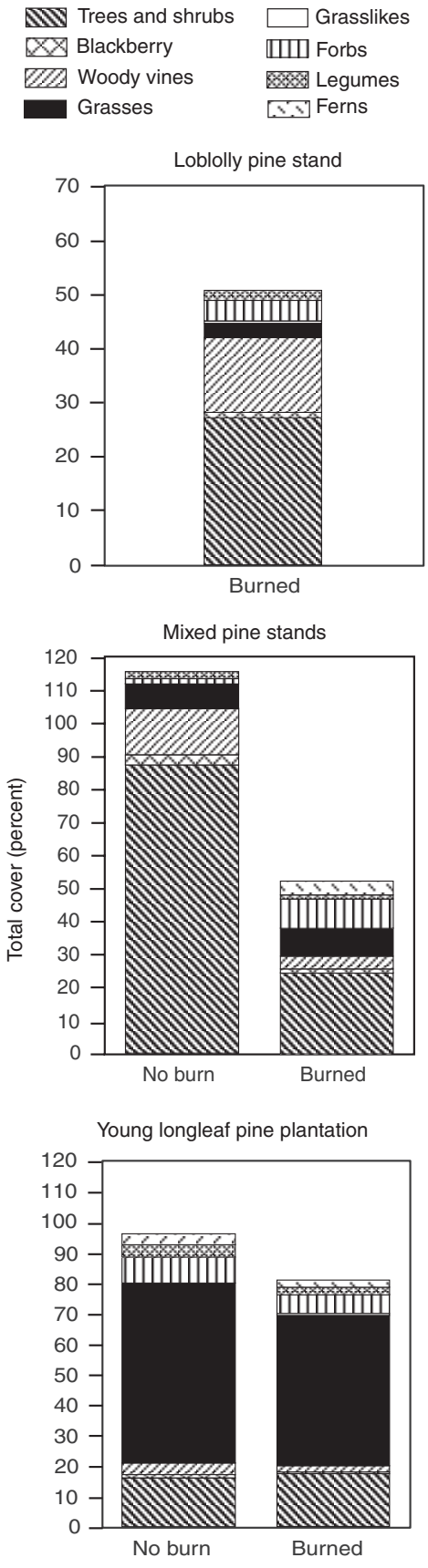

Figure 2—Percent cover of the understory vegetation by taxa on the burned and unburned portions of each forest type 6 weeks after the May 2001 burns.

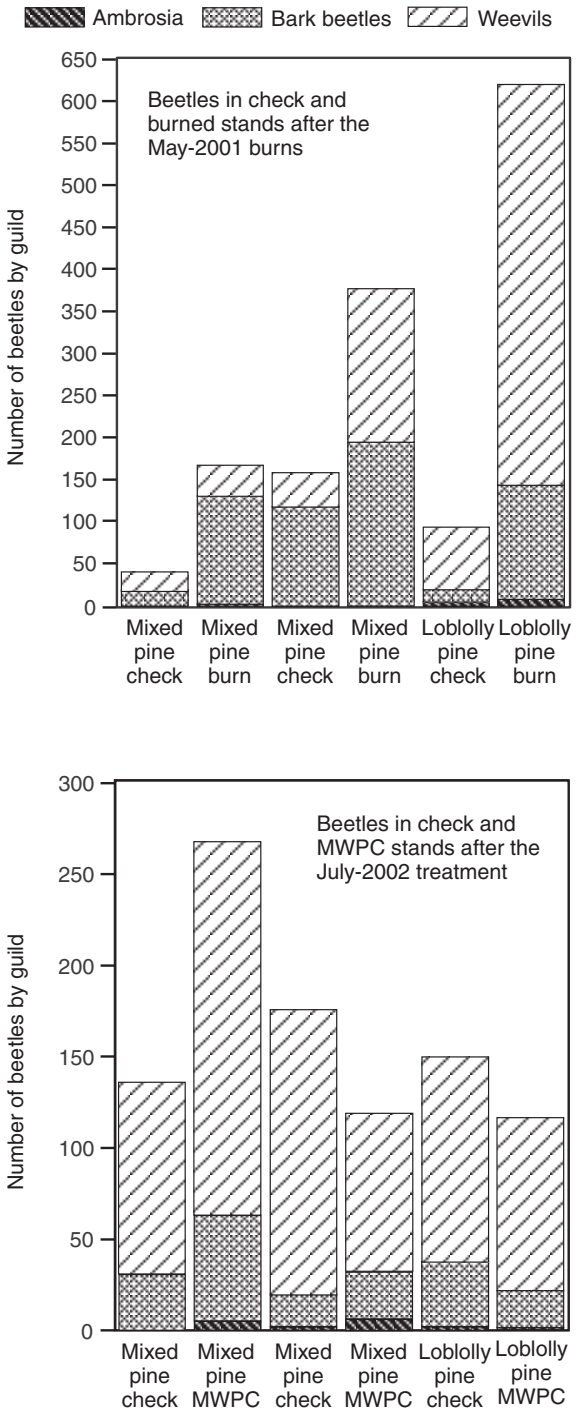

Figure 3—Number of beetles captured by guild after prescribed burning in May 2001 (top) and mechanical woody plant control (MWPC) in July 2002 (bottom).

In the general landscape, we recommend that loblolly pine stands be thinned and repeatedly prescribed burned; as well, MWPC should be applied to restore rich herbaceous plant communities dominated by grasses. After that, these sites should be clearcut and planted to longleaf pine. Prescribed burning should continue after planting, beginning in the second growing season, to maintain longleaf pine plantations with grass-dominated understories.

Longleaf pine naturally develops uneven-aged stand structures, and widespread uneven-aged landscapes are again possible if reserves of longleaf pine are intermixed with gap openings or regenerated areas. We recommend that mixed pine sites be thinned and burned with MWPC used to reduce the stature of understory brush. Eventually, the loblolly pine should be harvested in these mixed pine stands and the longleaf pine retained as a seed source. To ensure timely regeneration, longleaf seedlings should be planted under the retained longleaf pine. Prescribed burning should again be applied beginning in the second growing season after planting. This practice should result in the desired uneven-aged structure with longleaf pine-dominated overstories and rich herbaceous plant communities in the understories.

ACKNOWLEDGMENTS

The Joint Fire Science Program, Boise, ID, funds this project.

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A COMPARISON OF THE ECOLOGICAL EFFECTS OF HERBICIDE AND PRESCRIBED FIRE IN A MATURE LONGLEAF PINE FOREST: RESPONSE OF JUVENILE AND OVERSTORY PINE

Jennifer L. Gagnon and Steven B. Jack[1]

Abstract—Prescribed fire may be removed as a forest management tool by regulatory agencies concerned about air quality issues. Herbicides have been proposed as substitutes for prescribed fires in southern pine forests, but we are aware of no studies that examine the effects of herbicide application in mature, fire-maintained longleaf pine (*Pinus palustris* Mill.) forests. We compared the effects of prescribed fire (F), herbicide application (Velpar®L) (H), and a combination treatment (F+H) in a mature longleaf pine forest with a 60+ year history of prescribed fire. The responses of naturally regenerated juvenile longleaf pine and overstory trees were monitored for 3 years. Juveniles receiving the F+H treatment had the highest mortality; juveniles in the H treatment were the largest, with the highest percentage (134) growing into the sapling class. Growth response of the mature trees was not consistent among years. Overstory hardwood mortality was over 60 percent in the F+H and H treatments.

INTRODUCTION

Historically, fire was a frequent natural disturbance in longleaf pine (*Pinus palustris* Mill.) ecosystems in the Southeastern United States (Glitzenstein and others 1995, Landers and others 1995, Wahlenberg 1946). Disturbances from frequent, low intensity fires are essential to maintain the structure, diversity, and function of this forest type. Specifically, fire: (1) reduces fuels, minimizing wildfire incidence (Brockway and Lewis 1997, Brockway and Outcalt 2000, Wahlenberg 1946, Lemon 1949); (2) exposes a bare mineral soil seedbed necessary for longleaf pine regeneration (Brockway and Lewis 1997, Brockway and Outcalt 2000, Hodgkins 1958, Lemon 1949, Provencher and others 2001, Rebertus and others 1989, Wahlenberg 1946); (3) prevents hardwood encroachment (Brockway and Lewis 1997, Brockway and Outcalt 2000, Brockway and others 1998, Heyward 1939, Lemon 1949, Rebertus and others 1989, Wahlenberg 1946); (4) promotes diversity of understory species and flowering of certain species (such as wiregrass [*Aristida beyrichiana* Trin. & Rupr.); Mulligan and others 2002]; (5) provides habitat for wildlife, including rare and endangered species (Brockway and Lewis 1997, Brockway and Outcalt 2000); and (6) controls brown spot needle blight infection (Brockway and Lewis 1997, Brockway and Outcalt 2000, Lemon 1949, Rebertus and others 1989, Wahlenberg 1946).

Given the historical and ecological importance of fire in the region, prescribed fire has become an important tool for managing longleaf pine forests (Glitzenstein and others 1995, Landers and others 1995). However, potential restrictions on the use of prescribed fire, due to health and safety concerns regarding particulate and smoke production, have emphasized the need to look at alternatives. One such alternative may be herbicides. Herbicides have been widely used in forestry over the past 2 to 3 decades in intensively managed forests, where the primary management objective is fiber production (Haywood 1994, Haywood and Tiarks 1990). Herbicides have been shown to: (1) increase tree growth by controlling non-crop vegetation (Haywood 1994, Haywood and Tiarks 1990); improve habitat for certain wildlife species (McComb and Hurst 1987); (2) control hardwood competition (Haywood and Tiarks 1990, McComb and Hurst 1987); and (3) release seedlings from competing vegetation (Haywood and Tiarks 1990, McComb and Hurst 1987).

To date, little or no research has addressed the ecological impacts of herbicide treatment in mature mesic longleaf pine forests, and we are aware of only one study (Chen and others 1977) that directly compares the effects of herbicides and prescribed fire in mature or semi-mature forests. We initiated this study to evaluate the relative effects of herbicide application, as compared to prescribed fire, on the control of vegetative competition, impacts on native flora and fauna, and on the ecological function of mature longleaf pine forests. This study was not designed to examine the efficacy of herbicide in controlling hardwoods or maximizing growth rates but rather to compare the effects of herbicide relative to prescribed fire.

Specifically the objectives of this paper were to: (1) compare the growth and survival of longleaf pine juveniles to prescribed fire and herbicide application; and (2) compare the growth and survival of overstory trees (including both pine and hardwood) to prescribed fire and herbicide application. Our hypothesis was that growth and survival of both the juveniles and overstory would be similar among the treatments. Other ecological responses (e.g., biomass accumulation, canopy openness, species richness, nitrogen cycling, litter decomposition, and wildlife) were also monitored, but these data are not presented.

METHODS

Study Site

The study was conducted at the Joseph W. Jones Ecological Research Center, at Ichauway, located in southwestern Georgia, U.S.A. in the lower Gulf Coastal

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Plain (31° 13'N, 84° 29'W). The 11,600 ha property contains approximately 7,500 ha of longleaf pine. The study plots were located on old-field mesic sites (areas with little or no wiregrass) dominated by naturally regenerated second growth longleaf pine, approximately 70+ years old. Historically, frequent prescribed surface fires have been used to manage the sites. Dominant soil types range from somewhat poorly drained to somewhat excessively drained Ultisols.

Study Design

The study used a randomized complete block design with four replications of three treatments: 1. F = fire (applied June, 2000); 2. H = herbicide (hexazinone; Velpar® L spot applied on a 1.2- x 1.8-m grid at a rate of 2.5 L ha^{-1}, February, 2000). This particular herbicide treatment was chosen to minimize impact on groundcover plants and diversity, not to maximize hardwood control; and 3. F+H = fire + herbicide. Blocks were a minimum of 8 ha, and each treatment was represented once within each block. Ten 0.10-ha circular subplots were established within each treatment plot (n = 40 subplots per treatment) to monitor ecological effects. In 1999, pretreatment data were collected. All plots were burned in the summer (July-August) of 2002. Final juvenile and overstory measurements were made in the fall of 2002, following the prescribed fire.

Measurements

Juveniles—Within each treatment plot, 8 subplots with advanced natural longleaf pine regeneration were identified as regeneration subplots (n = 24 regeneration subplots total). Within each regeneration subplot, 20 seedlings were tagged for repeated measurements. The seedlings were selected so that the number of trees in each of three height classes was approximately equal (height class 1 = grass stage, less than 1 m tall; height class 2 = rocket stage, greater than 1 m but less than 2 m tall; height class 3 = saplings, greater than 2 m tall and diameter at breast height (d.b.h.) less than 10 cm. All regeneration was assumed to be from the 1987 seed crop (age 12 years at study establishment). End of growing season measurements were made in 1999 (pretreatment) and annually thereafter. Measurements included height (to tip of bud) using a height pole and either root collar diameter (for seedlings in height classes 1 and 2) or d.b.h. (for seedlings in height class 3). In 1999 and 2000, only one diameter measurement was taken for each juvenile tree; in 2001 and 2002, two diameter measurements, perpendicular to one another, were taken for each tree and averaged. The two measurement method takes into account the irregular shape of seedling stems and therefore may provide a more accurate estimate of diameter.

Overstory—Prior to treatment application (1999) and in 2001 and 2002, end of growing season height, d.b.h., species and status (living/dead) of all trees (d.b.h. > 6 cm) were recorded in each of the 0.10-ha circular subplots. Ingrowth (into the 6-cm diameter class) was also recorded in 2001 and 2002.

Data Analysis

SAS® software [V (9) of the SAS System for Windows] was used to analyze the data. Growth data were examined using a repeated measures design (Proc GLM). Pretreatment measurements were included as covariates in the analyses because there were strong correlations between pretreatment and post-treatment measurements as well as significant differences among pretreatment measurements. Survival data were examined using the Chi Square test for independence. Significance for all analyses was determined at $\alpha = 0.05$.

RESULTS

Juvenile Response

Growth—Mean seedling diameter decreased between 2000 and 2001. This decrease probably resulted from differences in measurement techniques (as described above) rather than from treatment effects. No significant differences in seedling diameter were observed in 2001 (fig. 1a). In 2002, however, seedling diameters in the H treatment were significantly larger than in the F and F+H treatments (F = 4.3 cm, F+H = 4.2 cm, and H = 4.5 cm; $p = 0.0171$). No significant height differences were observed in 2000 (fig. 1b); however, in 2001 and 2002, seedlings in the F and F+H treatments were significantly shorter than seedlings in the H treatment (e.g., 2002: F = 3.1 m, F+H = 3.0 m, and H = 3.5 m; $p < 0.0001$).

Survival and ingrowth—Low seedling mortality was observed in 2000 (fig. 1c). By 2001, however, the Chi-Square test for independence indicated that seedling survival was highly dependent upon treatment ($p = 0.0147$). The highest survival rates were in the F and the H treatments (94 and 96 percent, respectively) and lowest in the F+H treatment (87 percent). The differences were further evident in 2002 (F = 92 percent, F+H = 82 percent and F+H = 92 percent; $p = 0.0043$). The percentage of seedlings leaving the grass stage (height class 1) and initiating height growth (height class 2) was inconsistent over the course of the study (data not shown); in 2002, the percentage of juveniles leaving the grass stage was highest for the F+H and H treatments (F = 72 percent, F+H = 82 percent and H = 82 percent). The increase in percentage of juveniles in the sapling stage (height class 3) was consistently highest for the H treatment, and consistently lowest for the F+H treatment (e.g., in 2002, F = 121 percent, F+H = 79 percent, and H = 134 percent).

Overstory Response

Growth—Longleaf pine was the dominant pine species in the overstory. The most dominant hardwood species were southern red oak (*Quercus falcata* Michaux), laurel oak (Q. *hemisphaerica* Bartram ex Wild.), and water oak (Q. *nigra* L.). Pine diameters were not significantly different among the treatments (fig. 2a). In contrast, 2001 mean hardwood diameters in the F+H treatment were significantly smaller (F = 26.4 cm, F+H = 25.3 cm and H = 26.1 cm; $p = 0.0006$); however, by 2002 these differences were no longer significant.

Pine total height varied significantly, but inconsistently, among the treatments in both 2001 (F = 22.9 m, F+H = 23.1 m and H = 23.3 m; $p = 0.0034$) and 2002 (F = 23.3 m, F+H = 23.6 m and H = 23.5 m; $p = 0.0239$); (fig. 2b). The shortest trees were consistently in the F treatment.

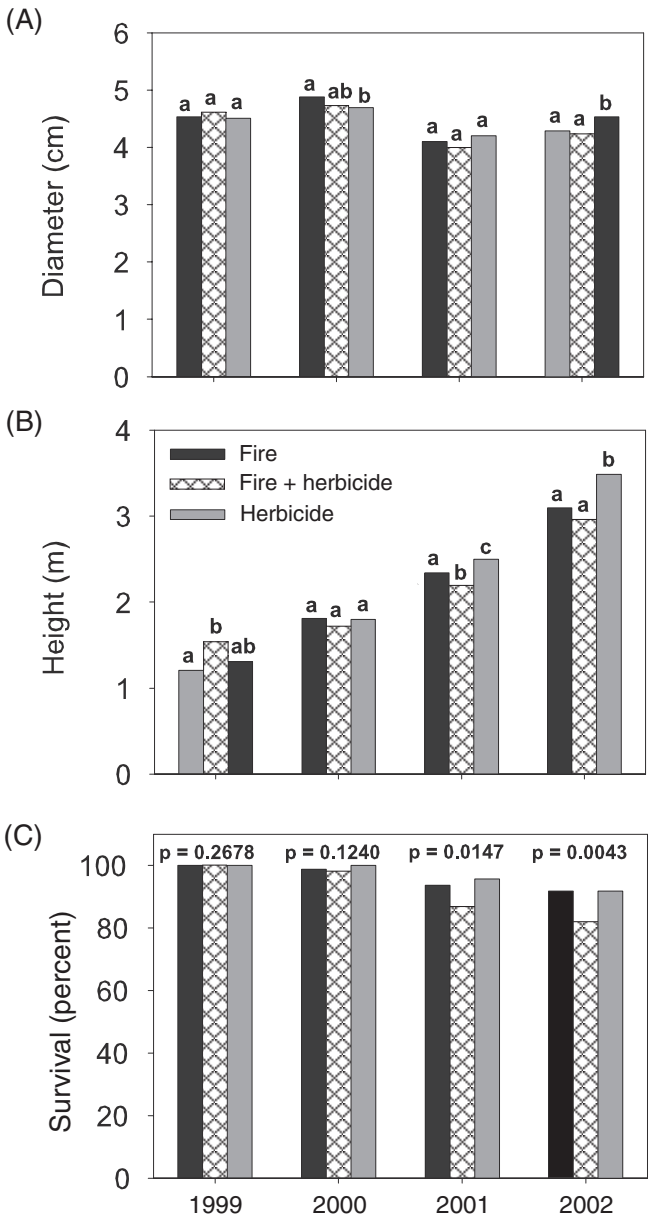

Figure 1—Longleaf pine seedling (a) diameters (b) heights, and (c) survival by year and treatment. Different letters denote significant differences among treatments at $\alpha = 0.05$. P-values are from the Chi-Square test for independence.

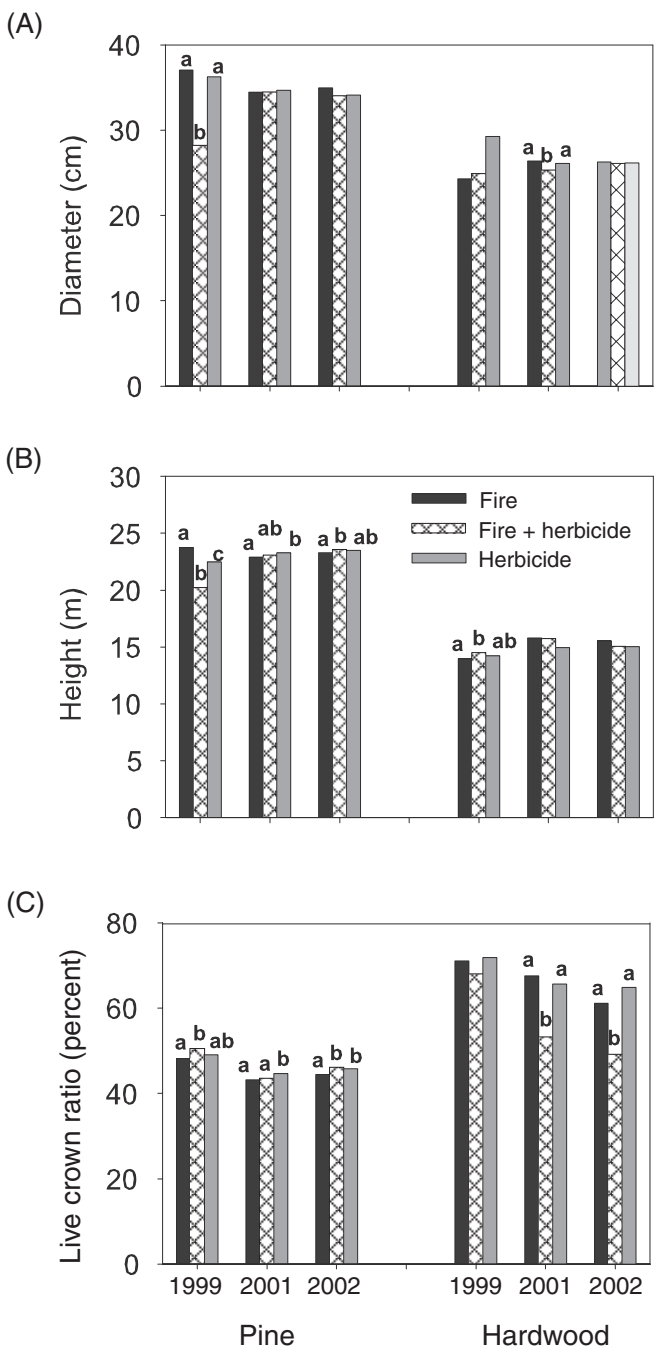

Figure 2—Overstory (a) diameters (b) heights, and (c) live crown ratios by year, treatment, and species group. Different letters denote significant difference at $\alpha = 0.05$. P-values are from the Chi-Square test for independence.

Hardwood total heights were not significantly different among treatments.

Pine live crown ratio (LCR) was significantly different in both 2001 (F = 43.2 percent, F+H = 43.6 percent and H = 44.7 percent; $p = 0.0401$) and 2002 (F = 44.4 percent, F+H = 46.1 percent and H = 45.8 percent; $p = 0.0069$) (fig. 2c). Pine LCR was consistently significantly lower in the F treatment compared to the F+H and H treatments. Hardwood LCR was also significantly different among the treatments in both 2001 (F = 68 percent, F+H = 53 percent and H = 66 percent; $p < 0.0001$) and 2002 (F = 61 percent, F+H = 49 percent and H = 65 percent; $p < 0.0001$), but unlike the pines, was significantly lower in the F+H treatment.

Survival and ingrowth—None of the treatments had a detrimental effect on overstory pine survival (in 2002, mortality was less than 3 percent for each of the treatments) (fig. 3a). In contrast, hardwood mortality was high in the F+H and H treatments (F = 2 percent, F+H = 63 percent and H = 70 percent). Pine ingrowth into the 6 cm diameter class was greatest for the F+H treatment and lowest for the H treatment (F = 70 trees per ha (TPH), F+H = 130 TPH and H = 10 TPH) (fig. 3b). Hardwood ingrowth was greatest in the F treatment and lowest in the H treatment (F = 110 TPH, F+H = 40 TPH and H = 20 TPH).

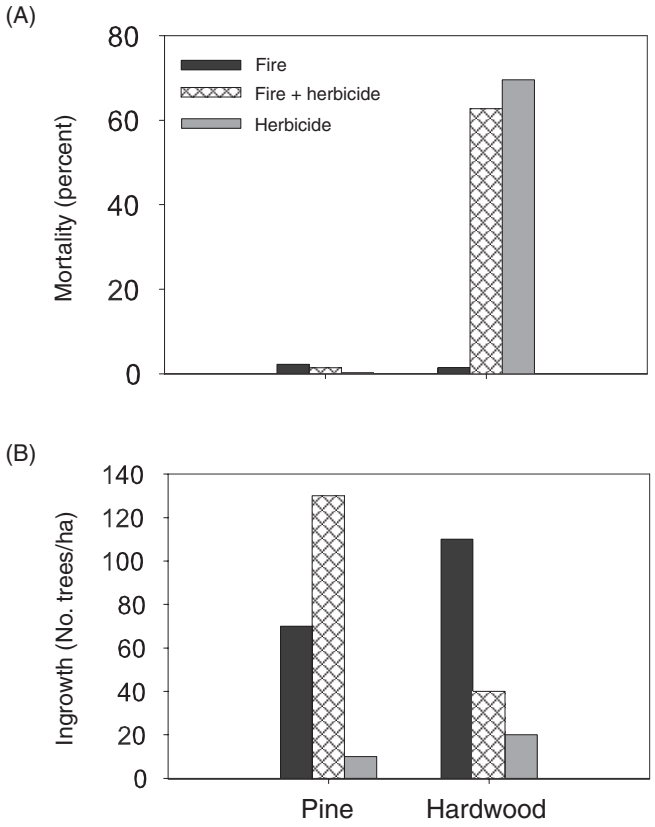

Figure 3—Pine and hardwood (a) overstory mortality and (b) ingrowth into the 6 cm diameter class, by treatment, in 2002. P-values are from the Chi-Square test for independence.

DISCUSSION

Prescribed fire is the main management tool in mesic longleaf pine ecosystems in the Southeastern United States. Recently, concern over the safety of using prescribed fire, particularly near urban areas, has indicated the need to explore alternative management tools. One such tool is herbicide application. Chen and others (1977) compared the effects of fire to the effects of herbicide application in loblolly-shortleaf pine (*Pinus taeda* L., *P. echinata* Mill.) forests; however the effects of these treatments on mature mesic longleaf pine forests have not been directly compared. This paper presents a portion of a larger study designed to compare the ecological effects of the treatments. The F treatment served as the control because repeated prescribed fires have been the standard management tool in this forest for over 60 years. As such, the discussion of the results will compare effects of the F+H and H treatments relative to the F treatment.

Results of this study suggested that if maximizing pine tree growth and survival and top-killing overstory hardwoods were the main management objectives, then herbicide application alone was an effective management tool. The H treatment increased seedling height and diameter growth, while maintaining seedling survival at levels comparable to the F treatment. In addition, the H treatment did not have a negative effect on overstory pine growth or survival but effectively top-killed overstory hardwoods. In mature longleaf pine forests, however, the management objectives are numerous, and maintenance of biodiversity, ecosystem function, wildlife habitat (particularly for rare and endangered species), and forest structure (i.e., open canopy, little or no midstory) may take precedence over maximizing pine growth.

Preliminary results from other aspects of this study indicated other management objectives were not being met when herbicide was used in place of prescribed fire. One problem was related to the method of herbicide application. The spot application was effective in top-killing overstory hardwoods with large root systems, which ensured contact with the herbicide. However, understory hardwoods with smaller root systems did not necessarily make contact with the herbicide. The death of the large trees released the smaller stems, including stems of resistant species, such as sassafras [*Sassafras albidum* (Nutt.) Nees]. Although this trend was not apparent in the ingrowth data presented in this paper, standing biomass data (not presented) showed an increase in woody midstory biomass in the H treatment (F = 163 g m^{-2} and H = 360 g m^{-2}). Even if a broadcast herbicide application is used, in the absence of prescribed fire, repeated herbicide treatments would be needed on a regular basis to maintain control of hardwoods.

Another problem associated with the H treatment was a significant increase in debris biomass (F = 3316 g m^{-2}, F+H = 3418 g m^{-2}, and H = 4217 g m^{-2}) and total biomass (F = 3741 g m^{-2}, F+H = 3743 g m^{-2} and H = 4817 g m^{-2}) in these plots compared to the F and F+H plots. In the absence of prescribed fire, biomass would continue to accumulate, thereby increasing fuel loads and potential for wildfire and eventually rendering the use of prescribed fire difficult and dangerous.

Brockway and Outcalt (2000) and Provencher and others (2001) demonstrated that rapid restoration on xeric sandhill sites could be achieved by using a combination of hexazinone application and prescribed fire. Our results suggested that the F+H treatment was useful in restoring mesic longleaf pine forests. Although there were some detrimental effects of this treatment on juveniles, survival remained above 80 percent 2 years after treatment. The F+H treatment could be used to effectively remove overstory hardwoods (a single application top-killed greater than 60 percent of the overstory hardwoods), while preventing smaller hardwood stems from growing into the midstory. Hexazinone resistant species, such as sassafras, would also be controlled. Repeated prescribed fire could be used to maintain the forest after a single herbicide application.

CONCLUSION

The results of this study, when examined apart from other ecosystem effects, suggested that herbicide application was a beneficial and perhaps suitable substitute for fire in mature longleaf pine ecosystems, at least for encouraging juvenile growth and removing hardwoods from the overstory. However, the ecological effects on the entire ecosystem need to be considered when making management decisions. Other data from this study, which were not presented here, showed an increase in woody midstory

biomass as well as significant increases in debris and total biomass; biomass would continue to accumulate in the absence of fire. Over time, these changes would increase fire risk and result in larger scale changes in the longleaf pine ecosystem. The F+H treatment may be the most effective in rapidly restoring degraded sites, when followed by a prescription of regular prescribed fire.

ACKNOWLEDGMENTS

Special thanks are extended to the Joseph W. Jones Ecological Research Center for funding this project. Thanks are also extended to the conservation staff for conducting the prescribed fires and to Mark Atwater of Weed Control Unlimited for advice on and application of the herbicide treatments. The following people provided assistance with plot establishment, field work and data entry: M.C.P. Sheffield, D.J. McConville, D. Davis, S. Odom, C. Ward, and A. DeLong.

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ESTABLISHING LONGLEAF PINE SEEDLINGS ON AGRICULTURAL FIELDS AND PASTURES

Mark J. Hainds[1]

Abstract—Acres planted to longleaf pine (*Pinus palustris*) increased annually through the 1990s until 2000 with peak plantings exceeding 110 million seedlings annually. Many of these longleaf seedlings were planted on agricultural crop fields and pastures. Agricultural areas have unique characteristics that can make them more challenging to successfully plant than comparable cutover sites. Seedlings planted on agricultural sites may suffer increased mortality from insect predation, disease, competition, and inhospitable soil conditions. Inadequate knowledge of longleaf pine's unique requirements on agricultural sites has led to many avoidable planting failures. Adequate site preparation, herbaceous release, and planting methods are critical for the successful establishment of longleaf on old fields and pastures. Combinations of site preparation and herbaceous release that have proven to be superior in the artificial regeneration of longleaf pine on agricultural sites will be discussed in this paper. Results from 4 herbicide screening trials and a site preparation study are included.

INTRODUCTION

The Longleaf Alliance was formed in 1995. Tens-of-thousands of agricultural acres were enrolled in the Conservation Reserve Program (CRP) at approximately the same time. The Longleaf Alliance played a crucial role in educating and informing CRP participants about the many benefits and challenges unique to longleaf pine (*Pinus palustris* Mill). Unfortunately, the best available information was often inadequate, and success rates varied considerably. With the benefits of hindsight and much experience, we believe that most planting failures were avoidable. Furthermore, many planting failures were attributed to factors that may not have played a role in seedling mortality on a given site.

Even without the CRP, millions of longleaf pine seedlings are planted annually on agricultural sites across the Southeastern United States, often with mixed success. Longleaf pine is selected as the primary tree species on many of these agricultural sites because of an increased interest from foresters, agency personnel, and landowners. Additionally, several State and Federal cost-share programs have monetary and regulatory incentives for longleaf that are not available for other southern pines species.

A new CRP enrollment has been authorized for 2003. In all likelihood, tens-of-thousands of additional acres will be enrolled in the CRP in the near future. If we have not learned our lessons from plantings in the late 90s, we are doomed to repeat many mistakes that were made during the initial CRP longleaf plantings—at considerable expense to landowners, State agencies, and the Federal Government.

The Longleaf Alliance has a unique advantage in that it is a regional organization with members from every State in longleaf pine's natural range. The alliance works directly with State forestry commissions, the U.S. Department of Agriculture, Forest Service, the Natural Resource Conservation Service, the Farm Service Agency, forestry consultants, herbicide applicators, tree planters, and landowners from across the Southeastern United States. Alliance personnel have witnessed almost every possible combination of site preparation, seedling stock, and herbaceous release on a variety of soil types from North Carolina to Texas. This wide-ranging experience has allowed us to work with others to identify many of the leading factors in longleaf seedling mortality.

SITE SELECTION

Before planting an agricultural field or pasture, it is important to determine if the site is appropriate for longleaf pine. Some sites are inappropriate and repeated planting failures are preordained. We do not recommend planting longleaf pine on sites that have high pH/basic soils (> 7.0 pH), excessive soil nutrients, or excessively wet soils.

High pH (Basic) Soils

The majority of soils across the Southeastern United States are acidic in nature and acceptable for longleaf pine seedling establishment. However, many agricultural sites have had their soil pH artificially raised by repeated applications of lime. The alliance has received reports of tomato fields in north-central Florida with pH readings approaching 8.0. Planting failures are the norm for any southern pine species on these sites. It could take many years for the soil to reach an acceptable pH for longleaf seedling establishment. Other soils are naturally basic (> 7.0 pH)—in particular, many prairie type soils in central Alabama and Mississippi. Experience has shown that it is very difficult to successfully establish longleaf pine on soils that have a pH greater than 7.0.

Excessive Soil Nutrients

Some areas have become so nutrientloaded that seedlings pick up toxic concentrations of normally beneficial nutrients. The alliance has visited, or received reports, concerning sites where large amounts of chicken litter were deposited or cattle catch pens were located. On these nutrient-loaded sites, longleaf seedling mortality approached 100 percent during the first growing season.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Excessively Wet Sites

Ponded soil types are typically problematical. Seedling mortality increased dramatically when seedlings were under water for more than a few days. Mortality can be reduced by planting seedlings with most of the plug protruding above the soil surface. However, excessively wet soils (Pelhams & Gradies) are generally ill suited for longleaf pine.

BAREROOT OR CONTAINER

After determining the site is appropriate, selection of seedling stock is the next important step. Longleaf seedlings are grown and planted as both bareroot and container-grown seedlings. Seedling survival varies considerably based upon seedling quality and, to some degree, on seedling type. A 1995 survey (Boyette 1995) found that foresters, tree planters, and landowners using container-grown stock averaged 85-percent survival but only 65-percent survival using bareroot stock. Although some tree planters are consistently successful planting bareroot seedlings, the trend has been towards the use of container-grown seedlings (table 1). The successful establishment of container-grown seedlings is the focus of this paper.

Inadequate containers were an early problem for a relatively new industry producing container-grown longleaf seedlings. The absence of ribs in some containers led to root spiraling, which is extremely detrimental to seedling survival, growth, and form. Also, longleaf seedlings were occasionally grown in containers that were too small to produce a quality seedling.

Another early problem was the absence of seedling standards. Seedlings were often shipped with small root collar diameters (RCD), poor root systems, diseased foliage, and with weeds in the plug. In response to the lack of seedling standards, The Longleaf Alliance cooperated with the USDA Forest Service to produce a set of interim standards for growing seedlings in containters (Barnett and others 2002). This publication has recommendations for ribbed containers, minimum root collar diameters (1/4 inch), plug attributes, foliage attributes, minimum container volumes and depths, and other characteristics to look for in a quality longleaf seedling.

There are several different types or classes of seedlings in a typical lot of longleaf seedlings. The Longleaf Alliance installed two studies to identify easy diagnostics that would allow sorting out of seedlings that would not survive and grow well (Barnett and others 2002). Study sites were installed in or near Monroeville and Samson, AL. Seedling types utilized in these studies included: hybrids (or seedlings that looked like hybrids), doubles (two seedlings per plug), culls/floppies, and good-quality seedlings without weeds in the plug. Survival was assessed approximately 6 months to 1 year postplanting (table 2). Culls or "floppies" were seedlings in which the plug "drooped" or would not hold itself parallel to the ground when held by the terminal bud.

Table 1—Production of bareroot and container-grown longleaf pine seedlings over a 6 year period

	Bareroot	Container	Percent[a]
	- - millions of seedlings - -		
1996	30.2	31.1	51
1997	27.6	36.3	57
1998	25.0	42.6	63
1999	26.2	56.4	68
2000	32.6	82.3	72
2001	23.8	73.2	75

[a] Container-grown seedlings as a percent of total longleaf pine seedling production.

Table 2—Survival of longleaf pine seedlings by seedling type

Site	Good	Double	Floppy	Hybrid
	- - - - - - - - - - percent - - - - - - - - - -			
Monroeville				
Age 1 year	75	N/A	21	64
Samson				
Age 6 months	91	96	80	81

As expected, good-quality seedlings demonstrated some of the best survival rates. Likewise, doubles did very well at the Samson study site but were not included at the Monroeville study site. Hybrid seedlings had lower survival rates than good quality seedlings. Floppies had the lowest survival rates, doing much worse on the Monroeville site but only slightly worse than good-quality seedlings on the Samson site. These findings are in line with those of Barnett and others (2002)*:* "Seedlings that fail to meet the criteria for the preferred category may survive and grow well under favorable site conditions." The Samson site was planted December 14, allowing seedlings to establish a better root system than the Monroeville seedlings, which were planted February 21. It is likely that planting dates were an important factor in the lower overall survival of seedlings on the Monroeville site and the abysmal performance of the floppy seedlings in Monroeville.

From these two studies and previous work done by the USDA Forest Service, we recommend that landowners or foresters:

1. Sort through seedlings boxes before delivering to the tree planter.
2. Establish counts of good quality seedlings per box.
3. Return boxes to the nursery if an excessive number of culls are found.
4. Request additional seedlings if your seedling count is short.

SITE PREPARATION

Over the past several years, the alliance has witnessed and directly participated in many attempts to establish longleaf pine in pastures or agricultural sites with significant components of perennial pasture grasses including bahia (*Paspalum notatum* Fluegge), fescue (*Festuca arundinacea* Schreb.), and bermuda grass [*Cynodon dactylon* (L.) Pers]. Most pasture plantings ended in failure. It was soon

established that grasses had to be removed or controlled through site preparation prior to planting. Planting seedlings directly into pastures with the intention of controlling grasses through a postplanting herbaceous release was a recipe for failure.

The Longleaf Alliance addressed this problem in a 1998 study entitled "Comparison of Site Preparation Methods and Herbaceous Releases for Longleaf Pine Establishment in an Old Pecan Orchard". The study site was located in Covington County, AL. Soils were sandy loams with a history of frequent liming and fertilization. The site had a full compliment of old-field broadleaves and grasses including bermuda, bahia, and crab grasses (*Digitaria spp.*) and many other competitive old-field weed species. Three site preparations were tested in this study: scalping and subsoiling, broadcast chemical (glyphosate & imazapyr) plus subsoiling, and check or subsoiling only plots. This study utilized a randomized complete block design with four replications. The main plot treatment was the site preparation, and subplot treatments were herbaceous releases. Site preparation was completed in the fall of 1998, and container-grown longleaf were hand-planted in January 1999. After planting, seedlings were released in April and May of 1999. Eleven herbaceous release treatments were applied (table 3). Survival was assessed in the first and second growing seasons (table 4). Differences were significant and increased with time postplanting. Consistent with work previously conducted in Florida (Barnard and others 1995), survival and growth were significantly better on scalped plots than on check (subsoil only) plots. Survival and growth of longleaf were also significantly better on scalped vs. chemically site-prepared plots.

HERBACEOUS RELEASE

The Longleaf Alliance has conducted four herbicide screening trials (as of December, 2002) with further demonstrations and trials planned in 2003. Results from the 11 herbaceous release treatments tested in the old pecan orchard were consistent with previous and subsequent screening trials. From these screening trials, our most consistently effective release is the "split" treatment. The split treatment is composed of an early preemergent application of Oust® at 2 ounces in March or April, followed by a postemergent

Table 3—Herbaceous release treatments (subplot treatments) used in site preparation comparison test

Product	Active ingredient	Timing of application
Ounces per acre		
Check	N/A	N/A
Velpar DF10.67/ Oust 2	hexazinone/sulfometuron	4/7/99
Oust 2	sulfometuron	4/7/99
Arsenal 4/ Oust 2	imazapyr/sulfometuron	4/7/99
Arsenal 4 /Oust 2	imazapyr/sulfometuron	5/12/99
Atrazine 64	atrazine	4/7/99
Atrazine 64/ Oust 2	atrazine/sulfometuron	4/7/99
Oust 2 & Arsenal 4	sulfometuron & imazapyr	4/7/99 & 5/12/99 (2 apps.)
Fusillade 24	fluazifop-P-butyl	4/7/99 & 5/12/99 (2 apps.)
Velpar DF 21.34	hexazinone	5/12/99
Velpar DF 10.67	hexazinone	4/7/99

Table 4—Seedling survival in the first and second growing seasons and costs per second-year seedling and per acre

	Check SP—subsoil only	Chemical SP + subsoil	Scalp SP + subsoil
Percent surviving (age 1)	64	72	88
Percent surviving (age 2)	46	61	82
Percent starting height growth (age 2)	30	54	72
Total $ per acre (site prep, planting, seedlings, and release)	175.00	245.00	195.00
$ per surviving seedling (age 2)	0.77	0.86	0.48
$ per seedling initiating height growth (age 2)	3.48	2.21	0.78

Arsenal® application of 4 to 6 ounces. Wait for grasses to emerge before applying the second Arsenal® application. On low fertility, sandy sites, the first Oust® application is often sufficient by itself. On more fertile sites, problematic grasses or weeds will generally start to appear approximately 6 weeks following the initial pre-emergent Oust® application. Typically the second postemergent treatment will go out between mid-May and late July.

Alternatively, for those who can only afford a single application, an Arsenal® (4 to 6 ounces)/Oust® (2 ounces) tank mix has consistently tested as one of the best herbaceous releases. We recommend the Arsenal®/Oust® tank mix be applied after May 1, as injury and seedling mortality have been associated with earlier preemergent applications.

Many people believe their herbaceous release application has led to increased seedling mortality. In many cases, they are probably correct. Reviewing the first four herbicide screening trials conducted by The Longleaf Alliance, we believe trends are emerging with late plantings or high pH soils or both and mortality related to soil-active herbicides such as Oust® or Oustar®. In general, seedling mortality will be greater with late plantings, agricultural sites, and high pH soils, regardless of the herbicide applied.

Root growth prior to herbaceous release appears to be the key in avoiding increased seedling mortality or injury following an herbaceous release. Seedlings appear to be more tolerant of soil-active herbicides if a good root system is established prior to the herbicide application. If an insufficient number of fine roots have exited the plug, expect increased mortality associated with early applications of soil-active herbicides. To avoid this, plant good-quality seedlings early in the planting season and excavate several seedlings prior to any herbicide application. If several roots have exited the plug, soil-active herbicides can be applied with less risk. If the root system is still confined to the plug, it is probably better to avoid soil-active herbicides that could potentially increase seedling mortality. Dig before you spray!

PLANTING DEPTH

Planting depth may be the most critical factor affecting seedling survival and growth. We believe that a large percentage of early unexplained planting failures were a direct result of planting seedlings too deep. Results from the first four planting depth studies installed by The Longleaf Alliance have been extremely consistent (table 5). When soil covers the terminal bud, seedling mortality increases dramatically, whereas seedling growth is set back with surviving seedlings.

Prior to this research, the "wick" theory was widely promoted across the Southeast. The premise of the wick theory is that seedlings planted with the plug exposed will "wick out" or desiccate and die. The wick theory promotes deep planting and the avoidance of exposing the plug at all costs. Studies conducted by The Longleaf Alliance show that in every study conducted thus far, seedlings planted with the plug exposed have outperformed seedlings planted with the terminal bud beneath the soil surface. Studies installed in 2002 and 2003 in Alabama, South Carolina, and Georgia are exploring this further.

TIME OF PLANTING

Historically, planting season has been restricted to the winter months with the majority of seedlings planted in December, January, or February. With the advent of container-grown seedlings, a longer planting season was advocated with some people delaying plantings until March. Although little research has been conducted on time-of-planting with container-grown seedlings, the majority of anecdotal evidence suggests that earlier plantings are more likely to succeed than later plantings. Given adequate soil moisture, The Longleaf Alliance recommends planting as early as October. In moist soils, longleaf seedlings frequently initiate root growth very quickly. Early planted container longleaf seedlings appear more tolerant of winter droughts than bareroot seedling stock. Seedlings planted early in the planting season have more developed root systems in spring and thus appear more tolerant of spring droughts and herbaceous competition. Seedlings planted in late February or March appear much less hardy and are more susceptible to injury or mortality from herbaceous release treatments, herbaceous competition, and spring or summer droughts. From plantings on or around the Solon Dixon Center, one good rain (> 1 inch) soon after planting is sufficient to ensure a successful establishment of container-grown longleaf seedlings on most sites.

Many people are unaware that summer planting is a viable option. The Longleaf Alliance has planted longleaf on several sites in May, June, and July of 2001 and 2002. Overall survival rates have averaged approximately 80 percent at 1 year postplanting. With this limited experience, we only recommend summer planting in areas where seasonal

Table 5—Mortality by planting depth from deep to shallow (height to terminal bud) 1 or 2 years post-planting

	Planting depth						
Study site	-3 CM	-1 CM	Level	+1 CM	+2 CM	+3 CM	+6 CM
	percent mortality						
Silvopasture	57	41	24		21		
Godwin	79	71	39		36		
Orchard		56	19	17	20		
Monroe			38			33	21

rainfall is high during the summer months. June and July are typically wet months along much of the Lower Coastal Plain. From our experience, summer planting is a good option for filling in mortality on winter plantings, as long as adequate soil moisture is present and competition has been controlled through an herbaceous release treatment.

SUMMARY

We conclude the following: Use good seedlings; scalp agricultural fields; plant as early as possible; plant shallow with the terminal bud well above the soil surface; release seedlings from herbaceous competition for increased growth; examine roots before applying soil-active herbicides; and interplant mortality (May-July) if soil moisture is adequate.

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FACTORS AFFECTING SURVIVAL OF LONGLEAF PINE SEEDLINGS

John S. Kush, Ralph S. Meldahl, and William D. Boyer[1]

Abstract—Longleaf pine may be managed most efficiently in large even-aged stands. Past research has shown that the effect of trees surrounding the openings (gaps) or the use of fire is a complicating factor, especially with small openings. Longleaf seedlings are considered more susceptible to fire under and nearer to standing trees, and seedling size, kind of fire, soil type, and exposure are important factors of concern. Two studies conducted in the early 1970s examined factors affecting survival of longleaf pine seedlings. One study followed longleaf pine survival growing in different patch sizes. Patch size had no effect on seedling survival, stocking, or mortality from prescribed burning. The second study examined the effects of fire, including fire treatment, soil type, wall exposure, or distance from the forest wall. There was no significant longleaf pine seedling mortality in relation to fire treatment, soil type, wall exposure, or distance from forest wall.

INTRODUCTION

Longleaf pine (*Pinus palustris* Mill.) ecosystems are considered to be in a perilous condition. A report by the U.S. Department of the Interior lists the longleaf pine ecosystem as the second-most threatened ecosystem in the United States. (Noss and others 1995). The original longleaf pine forest was self-perpetuating. It reproduced itself in openings in the overstory where young stands developed. The result was a parklike, uneven-aged forest, composed of many even-aged stands of varying sizes.

The character of the ecosystem is best maintained with natural regeneration, with optimum use of processes or treatments simulating the processes that have long maintained longleaf ecosystems over the millennia. However, no phase of longleaf pine management presents more complex and critical problems than does its reproduction. Solutions depend on understanding the prerequisites of the process, the characteristics of seed-bearing trees and longleaf pine seed crops, and the possible causes of failure after seed fall. Predicting seedling performance under varying levels of overstory competition is important for understanding the consequences of silvicultural systems.

Wahlenberg (1946), in his landmark text "Longleaf pine: Its use, ecology, regeneration, protection, growth, and management" devoted three chapters to the topic of longleaf pine regeneration—nearly one-quarter of the book. In his introduction he stated, "Where formerly it had complete possession of the land, it has often failed to reproduce; this failure has resulted in deterioration of land values in many localities". He started off his chapter "Problems of Natural Reproduction" with this: "Deliberate regeneration of longleaf pine has been rarely accomplished". The two major problems he identified for the frequent failure were: (1) fire, whether too frequent, killing recent regeneration, or too infrequent resulting in competition from other species; and (2) logging practices that left little or nothing on the ground or no seed trees.

Longleaf pine can be managed most efficiently in large even-aged stands. Such stands provide convenient units for prescribed burning, logging, and silvicultural operations. However, development of large even-aged stands does not meet the needs of all forest ownerships. Some landowners may desire to maintain the look that described the longleaf pine forests at the time of settlement—mature trees with regeneration occurring in small openings that may have been created by lightning or windthrow. In the case of small properties where a distribution of age classes is desired, relatively small stands must be developed. In recreation forests, and otherwise where aesthetics are important, large clearcut stands may not be desirable. In these, and related cases, small even-age patches or stands must be developed. A possible way of developing this form of forest would be small-patch clearcutting. However, there are many silvicultural problems in developing such a system. Past research has shown that the effect of trees surrounding openings (gaps) or the use of fire is a complicating factor. Longleaf pine seedlings are considered more susceptible to fire under and nearer to standing trees, and seedling size, kind of fire, soil type, fuel load, and exposure are important factors with which to be concerned.

Where a number of small stands or groups are developed in one burning unit, the use of prescribed fire is complicated. Seedlings are more susceptible to fire under and near overstory trees. Fire tolerance is related to age of seedling, and many age classes would be present. Early studies (Boyer 1963, Davis 1955) suggested that fire should be excluded from stands under or near a forest wall, but another study (Maple 1969) indicated that resistant, grass-stage seedlings can be burned under a wide range of overstory densities with a carefully prescribed, cool winter fire without appreciable damage.

To examine seedling survival in relation to gap size and fire type, two studies were carried out on the Escambia Experimental Forest (EEF) in Brewton, AL, in the early 1970s. The first study evaluated longleaf pine seedling survival and stocking in 1-acre, 1/2- acre, and 1/4- acre

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

patches. The second study was conducted to determine the effect of hot, moderate, and cool fires on longleaf pine seedlings in the resistant grass stage.

The Escambia Experimental Forest is a 3,000-acre field laboratory located in Escambia County, 7 miles south of Brewton, AL. It was established in 1947 by the United States Forest Service primarily to study problems associated with the ecology and management of longleaf pine forests. The T. R. Miller Mill Company of Brewton, AL, provided the land at no cost, under a 99-year lease. The U.S. Forest Service Silviculture Research Project on the campus of Auburn University now handles research activities and general administration of the forest. A little over 80 percent of the forest is in the longleaf pine type with the remainder in slash pine-hardwood bottoms. Research operations have developed many age classes, from newly germinated seedlings to stands with trees up to 160 years old. About 1,200 acres have been naturally regenerated, and more than half of this forest is in stands ranging from 40 to 55 years of age. No other location has the combinations of stand ages, sites, and conditions that are found on this Experimental Forest. To date, more than 200 publications have resulted from work conducted on the Escambia Experimental Forest.

METHODS

Patch-Size Study

The patches were established on the EEF during the winter of 1970-71. Patches were laid out, the competing vegetation was cut, and hardwood stumps of live trees were treated with 2,4-D amine to prevent sprouting. Within each patch, lines radiated in the four cardinal directions and pins were placed in the lines 4.7, 3.3, and 2.3 feet apart within the 1-acre, 1/2- acre, and 1/4- acre patch, respectively. Each pin was used as the center for a circular milacre plot for recording natural regeneration. If one or more natural longleaf pine seedlings were found on the milacre, it was recorded as stocked.

Longleaf pine 1-0 planting stock was carefully lifted and graded to remove all but grade 1 stock. Each seedling was planted within 3 inches of the pin laid out in each patch. Planting was completed on February 23, 1971, having been planted within 48 hours of lifting. The plots were examined in November of 1971, 1972, and 1973. The entire study area was burned on February 4, 1974, under relatively cool conditions. Final examination of the planted and natural seedlings was in April 1974, 2 months after being burned.

Fire Effects Study

Plots were laid out in December 1970 in six separate areas on the EEF. Three were on sandy soil and three on clay-based soils. Sandy-soil plots were characterized by loamy sand to 60 inches or more and were located on Alaga soil series. The clay-soil plots were located on Bowie series. They are characterized by a loamy sand or sandy loam surface soil underlain by a sandy clay loam subsoil at 12 to 14 inches. The sandy clay loam subsoil becomes mottled at 38 inches and extends to 78 inches or more.

No cutting of overstory timber was necessary on two plots located in existing openings. The overstory had to be cut in the other four to create the clearcut openings. Following logging, the area occupied by the seedling transects on all plots was strip mowed along the measurement transect with a rotary mower before pins to locate seedlings were placed.

In February 1971, 1-0 longleaf pine seedlings were planted immediately in front of each pin. The seedlings were dibble planted within 48 hours of lifting from the nursery. Seedlings were vigorous, grade one, and over one-half inch in diameter at the root collar.

The cool and moderate burns took place in January 1973 and the hot burns in May 1973. Plots were examined in November 1973, and the mortality the first year after the burns was recorded. Losses on the no-burn treatment, relatively minor, were subtracted from the total losses on the fire-treatment areas to determine fire losses.

RESULTS AND DISCUSSION

Patch-Size Study

Results based on the last two measurements indicated survival of planted stock after three growing seasons averaged 85 percent, varying from 71 percent on 1/2- acre plots to 95 percent on 1/4- acre plots. This survival is considered excellent for longleaf pine planted on nonprepared sites.

Milacre stocking of natural regeneration averaged 76 percent at the time of the November 1973 examination, ranging from 65 percent on the 1/2- acre plots to 85 percent on the 1/4- acre plots. As with the planted seedlings, stocking for natural regeneration was not related to patch size. Competing vegetation and other site factors were mostly responsible. The poorest stocking on a patch, 37 percent, was found where 45 percent of the seedlings were overtopped by brush. Natural reproduction on the 1/2- and 1/4-acre plots came mainly from the 1971 seed crop whereas the 1-acre plots were stocked with seedlings that originated under a shelterwood overstory before clearcutting.

Losses from burning were minor, averaging only 5 percent for planted stock. Milacre stocking of natural seedlings was reduced 5 percent by burning. Absence of needle cast in the clearcut openings undoubtedly was a favorable factor contributing to the lack of fire damage.

During the November 1973 examination, an estimate was made of the proportion of seedlings overtopped by brush. Averages were as follows: 1acre = 9 percent; one-half acre = 30 percent; and one-quarter acre = 31 percent. Overtopping ranged from 45 percent on the brushiest patch to 3 percent on the cleanest one. The brush problem was related to site and past treatment of the area. Less brush occurred on grassy ridge tops where advance reproduction was established under an overstory before clearcutting. Heaviest brush occurred on branch border areas where no advance reproduction was established, and past fires had not been hot enough to prevent the invasion of brush.

Although limited in scope, this study revealed some of the limitations and potentials of patch clearcutting. The minor losses from the dormant season fire suggest the possibility of using fire in uneven-aged burning blocks without expensive line plowing. This makes the use of fire with small patch clearcutting practical. A major problem appears to be the rapid regrowth of brush. In many situations, mechanical seedbed preparation will be essential. If a good seed crop is not on the surrounding forest wall at the time of clearcutting, it may be best to plant rather than wait for natural regeneration. One growing season should be allowed to elapse before planting to avoid damage from pales weevil.

Fire Effects Study

There were no major fire losses in relation to fire treatment, soil type, wall exposure, or distance from forest wall. Losses, however, were significantly higher on (the west side of) the east walls as opposed to (the east side of) the west walls in the hot fire treatment. However, differences barely reached significance at the 5-percent level and only averaged 8 percent, ranging from 0 percent to 16 percent. No significant effect on mortality by soil type, or proximity to the wall was revealed.

The minor fire losses were probably due to the character of the seedlings. They were large (over one-half inch at the root collar), vigorous, and in the fire resistant grass-stage, having not started height growth yet. The higher losses on (the west side of) the east wall in the hot fire were probably due to the drier fuel. Burning was done in the afternoon, and the fuel here was in full sunlight whereas the fuel out from the west wall was in the shade. The results show that seedlings in the large resistant grass stage can escape serious fire damage when prescribed fires burn through small patches of reproduction in clearcut openings. Smaller seedlings under more adverse weather conditions probably would be damaged more seriously. However, these results do suggest that carefully prescribed fire can be used where small groups of reproduction are developed in a burning unit of practical size.

CONCLUSIONS

Longleaf pine is a contradictory species. Results from research on one site may not be applicable to different sites and even similar sites. Longleaf pine was managed very successfully by nature for millennia. At times, we have failed miserably in our attempt to regenerate longleaf pine. The keys to its natural regeneration may be the previous management and its results and the proper use of fire. We need to take our cue from nature in our efforts to naturally regenerate longleaf pine.

Wahlenberg concluded the chapter with: “Mismanagement of longleaf pine has been the rule rather than the exception, due to the ignorance of the unique life history and incomplete knowledge of factors determining the life and death of seedlings and hence the succession of forest types”.

ACKNOWLEDGMENTS

The authors wish to acknowledge Thomas Croker and the staff of the Escambia Experimental Forest for the work they did in collecting the data. The work on the Escambia Experimental Forest could not have been conducted without the support of T.R. Miller Mill Company. They have provided use of the Escambia Experimental Forest for research purposes for more than 50 years and are gratefully acknowledged.

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DETERMINING THE CORRECT PLANTING DEPTH FOR CONTAINER-GROWN LONGLEAF PINE SEEDLINGS

Mark J. Hainds[1]

Abstract—The Longleaf Alliance installed four planting-depth studies from 1998 to 2002 to determine the optimal depth for container-grown longleaf pine (*Pinus palustris* Mill.) seedlings. Results indicate that deep planting significantly reduced seedling survival and growth. Results also indicate that longleaf is very tolerant of shallow planting whereby the plug is exposed at the time of planting, thus discrediting the "wick" theory. Planting-depth guidelines for most States may be incorrect. Emphasis should be shifted from depth of the plug to height of the terminal bud above the soil surface.

INTRODUCTION

Approximately 30 million container-grown longleaf pine (*Pinus palustris* Mill.) were planted annually in the Southeastern United States as early as 1996 (Hainds 2002). Approximately 45 million container-grown longleaf pine seedlings will be planted during the 2002-03 planting season (Hainds unpublished data). Despite these huge investments in artificial regeneration of longleaf pine, no research was done prior to 1998 that examined methods for planting container-grown longleaf pine seedlings.

In December 1998, The Longleaf Alliance installed the first planting-depth study to validate information related by tree planters and foresters who had considerable experience planting bareroot loblolly and slash pine. Common knowledge stressed that "deeper is better" regardless of the pine species being planted. Planting guidelines developed from these theories typically emphasized a narrow planting window with a major concern being the avoidance of shallow planting that exposed the plug. The prevailing theory was that an exposed plug would act as a "wick" (Larson 2002), drying out the plug and increasing seedling mortality. Furthermore, most guidelines allowed the terminal bud to be covered with soil at the time of planting, assuming that erosion will uncover the bud and allow unrestricted growth. Consequently, these planting guidelines encouraged deep planting.

Prior to this 1998 study, no research examining planting depth and container-grown longleaf pine seedling survival could be located in the existing literature. Initial findings from the 1998 study indicated that covering the terminal bud with soil was severely detrimental to seedling survival and growth (table 1), (Orchard Site). "Shallow" seedlings exhibited no ill effects from exposing the plug. Suspecting this finding was an anomaly, three subsequent planting-depth studies were installed over the following years.

METHODS

Study Designs

All four planting-depth studies utilized the randomized complete block design. Each study had 4 or 5 replications of each treatment (depth) and 14 seedlings per plot. Survival rates were assessed at 1 to 2 years postplanting.

Planting Methods, Soils, and Seedlings

All seedlings were planted by hand using either plug tools or OST planting bars (dibbles). Soils across all sites were sandy loams or loamy sands. The Monroe Study was unique in that soils were exceptionally wet with the seedlings often being under water following rainfall events. Seedlings were 4 ½-inch plugs on the Orchard Site and 6-inch plugs with the remaining three studies.

STUDY SITES

Orchard site (1998)—This study was installed in an old pecan orchard on the Solon Dixon Center in southern Alabama. Site preparation consisted of a scalping operation exposing a trench about 4 inches deep and 30 inches in width. Immediately after scalping, the site was ripped/subsoiled to an approximate depth of 16 inches. Seedlings were hand planted with a plug tool in December 1998. Four planting depths were examined:

Table 1—Percent mortality by planting depth from deep to shallow[a] (height to terminal bud)

Study site	-3 CM	-1 CM	Level	+1 CM	+2 CM	+3 CM	+6 CM
				percent			
Silvopasture	57	41	24		21		
Godwin	79	71	39		36		
Orchard		56	19	17	20		
Monroe			38			33	21

[a] Mortality assessed 1 or 2 years after planting.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

1. Exposed plug, terminal bud 2 cm above soil surface (+2 CM)
2. Exposed plug, terminal bud 1 cm above soil surface (+1 CM)
3. Plug covered - 1 cm below soil surface, terminal bud not covered (level)
4. Plug 2 cm below soil surface, terminal bud 1 cm deep (-1 CM).

Silvopasture site (2000)—Six-inch plug seedlings were planted with an OST dibble on December 7, 2000, on a cutover site that had minimal mechanical site preparation. Survival was assessed on June 10, 2002. Terminal bud position was used for treatment depths rather than plug position. The 4 treatments were:

1. Bud 3 cm (1.2 inches) beneath soil surface (-3 CM)
2. Terminal bud 1cm (0.4 inch) beneath soil surface (-1 CM)
3. Bud exposed at soil surface (level)
4. Bud 2 cm (0.8 inch) above soil surface (+2 CM).

Godwin site (2000)—Site preparation consisted of a scalping operation exposing a trench about 4 inches deep and 30 inches in width. Six-inch plug seedlings were planted with an OST bar on December 1, 2000, and survival was assessed on December 3, 2002. Terminal bud position was used for treatment depths rather than plug position. The 4 treatments were the same as for the Silvopasture site.

Monroe site (2002)—Site preparation consisted of a scalping operation exposing a trench about 4 inches deep and 30 inches in width. Six-inch plug seedlings were planted with an OST bar on February 21, 2002, and survival was assessed on February 18, 2003. Terminal bud position was used for treatment depths rather than plug position. The 3 treatments were:

1. Plug exposed, bud 1 cm (0.4 inch) above soil surface (+1 CM)
2. Terminal bud 3 cm (1.4 inches) above soil surface (+3 CM)
3. Terminal bud 6 cm (2.4 inches) above soil surface (+6 CM).

RESULTS AND DISCUSSION

Seedling survival and growth were negatively affected by deep planting (table 1). Mortality increased if the bud was covered at the time of planting or buds were subsequently covered by soil moving onto buds in scalped rows. In scalped furrows, seedlings planted with the bud at, or slightly above, the soil surface ended with the bud covered by soil moving into the scalped furrow. Approximately 1 inch of soil moved into 3- to 4-inches deep scalped furrows within 6 months of planting. If seedlings were not planted with the plug protruding at least 1.5 inches above the soil surface in deeper furrows, soil movement into the furrow and over the terminal bud may result in increased mortality and decreased growth rates of surviving seedlings. No significant increases in mortality were detected in seedlings planted with the plug exposed, even where approximately 5 cm of the plug was above the soil surface on the Monroe Site.

CONCLUSIONS

1. Deep planting, where the terminal bud is covered with soil, resulted in increased seedling mortality and reduced growth.
2. The wick theory is invalid. Container-grown longleaf pine seedlings appeared tolerant of shallow planting with the plug exposed.

NEW RECOMMENDATIONS FROM THE LONGLEAF ALLIANCE

Rather than focusing on depth of the plug, focus on anticipated position or depth of the terminal bud 6 months to 1 year postplanting.

1. On flat-planted sites, instruct tree planters to leave plug slightly exposed so that the terminal bud is above the soil surface.
2. On scalped sites, try to position the terminal bud approximately 2 inches above soil surface, leaving 1 to 1.5 inches of the plug exposed.
3. On extremely wet sites, position terminal bud > 2 inches above the soil surface, leaving 2 to 3 inches of the plug exposed.

ADDITIONAL STUDY

A fifth planting-depth study was installed at the Solon Dixon Center on a cutover site in July 2002. A sixth study was installed in Milledgeville, GA, in January 2003. Sites number 7 and 8 were planted February 4, 2003, in Lexington, SC. Finally, a ninth site was selected and planted in Denton, GA, on February 6, 2003. Additional studies will be installed with plugs protruding further above the soil surface on cutover sites. Sites with heavier soils should be examined in future replications. Also, different plug lengths and seedling root-collar diameters should be examined for tolerance of shallow planting.

SUMMARY

Seedlings planted with the plug protruding above the soil surface survived and grew at the best rates regardless of the site, environmental conditions, or plug length. Position of the terminal bud is more important that position of the plug. Seedlings planted with the terminal bud beneath the soil surface suffered increased mortality compared to seedlings with the terminal bud above the soil surface. Benefits of shallow planting appear to be more pronounced in areas where soil will move onto the seedling (i.e., scalped fields) and very wet sites. Seedlings planted with the plug exposed did not suffer increased mortality as previously supposed with the wick theory.

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CONTAINER-GROWN LONGLEAF PINE SEEDLING QUALITY

Mark J. Hainds and James P. Barnett[1]

Abstract—This study examines the comparative hardiness of various classes or grades of container-grown longleaf pine (*Pinus palustris* Mill.) seedlings. Most container longleaf seedlings are grown in small ribbed containers averaging 5 to 7 cubic inches in volume and 3 to 6 inches in depth. Great variability is often exhibited in typical lots of container-grown longleaf pine seedlings. Longleaf seedlings are usually sold on a per-thousand basis and an average lot of 1000 seedlings will contain "good" or "target" seedlings, "doubles" (two seedlings per plug), "floppies" or "culls", and "sonderegger" (hybrid loblolly x longleaf) seedlings. This study examines the relative survival rates of these four seedling types in the first growing season.

INTRODUCTION

This study was initiated to determine the feasibility of increasing longleaf pine (*Pinus palustris* Mill.) planting success by visually sorting through given lots of container-grown longleaf pine seedlings and removing nontarget seedlings. Most container longleaf seedlings are grown in small ribbed containers averaging 5 to 7 cubic inches in volume and 3 to 6 inches in depth (The Longleaf Alliance 2003). Typical seedlings are sown in the spring and form a well-rooted "plug" by late fall or early winter. Herein, these seedlings are referred to as "target" seedlings. Target seedlings met seedling quality standards as defined by Barnett and others (2002).

Some nurseries double-seed containers to insure an optimum percentage of cells are filled with viable seed, often resulting in two live seedlings per plug. These seedlings are herein referred to as "doubles." Other seedlings are suppressed in the container by surrounding seedlings that exhibit faster growth. Suppressed seedlings usually do not develop sufficient root collars or fine root systems to form a good plug and are typically referred to as "culls" or in this study as "floppies." Seedlings that did not meet the interim standards because of inadequate plugs were selected as floppies for this study. A final category of seedlings is hybrids between longleaf and loblolly. These hybrids are historically referred to as "sondereggers" (Walker and Wiant 1966). Sonderegger seedlings typically exhibit height growth while still in the container.

Longleaf seedlings are usually sold on a per-thousand basis, and an average lot of 1000 seedlings will contain target, double, floppy, and sonderegger seedlings. This paper examines relative survival rates of these four seedling types in the first growing season.

METHODS

Studies were installed on the Samson Site in southeastern Alabama and the Monroe Site in southwestern Alabama. A randomized complete block study design was utilized on both sites. Four replications of each block were planted with 20 longleaf pine seedlings per treatment. Seedlings were grown in 6-inch styroblock containers by two nurseries in south Georgia. Seedlings were separated into classes to examine survival and growth for different container-grown seedlings classifications. Seedlings classes were:

1. Good quality—seedlings with firm plugs and no visible diseases on the foliage
2. Floppies (culls)—seedlings whose plugs were not firm or solid enough to remain straight when held in a horizontal position. When held horizontally by the terminal bud, the seedling "flopped" over
3. Doubles—two seedlings per plug
4. Sondereggers—potentially hybrid seedlings that exhibited some stem elongation in the plug.

All four seedling types were utilized at the Samson Site. Doubles were not included at the Monroe Site. Prior to planting, both sites were scalped. Scalping was done with a three-point hitch fire plow. The scalped area was approximately 30 inches in width and 4 inches deep.

Seedlings were assessed for percent survival and overall appearance. Health was assessed based upon aboveground foliage. Scores were on a scale of 0 to 6. A perfect seedling scored 0, while a dead seedling scored 6. Average scores are given for surviving seedlings only: the lower the average score, the healthier the appearance of seedlings in a given treatment.

Samson Site

The study site had been unsuccessfully planted to bareroot longleaf seedlings 2 years prior to the study installation. The landowner and county forester attributed the previous planting failure to a spring drought following planting. Prior to the first longleaf planting, the site had been in cotton and peanut production. Seedlings were provided by Meek's Farms of Kite, GA. Seedlings were shipped to The Longleaf Alliance and planted within a few days of extraction and shipping. Seedlings were hand planted on December 14, 2001. Seedlings were band-sprayed with 2 ounces of Oust in April.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Monroe Site

This site is part of an Auburn University Agricultural Experiment Station and was in cotton production the year prior to study installation. Seedlings were provided by Simmons Tree Farm of Denton, GA. Seedlings were shipped to The Longleaf Alliance and planted approximately 1 week after extraction and shipping. Seedlings were hand planted on February 21, 2002, with dibble bars and plug tools. Seedlings were band-sprayed with 2 ounces of Oust in April.

RESULTS

Overall survival rates varied between the two sites (table 1). We attributed this to the earlier planting date on the Samson Site (December 14) as compared to the Monroe Site (February 21). Good quality seedlings excavated in April exhibited more developed root systems on the Samson Site, as compared to the Monroe Site.

Table 1—Percent surviving seedlings 6 months after planting

Site	Target/ good	Doubles	Sondereggers	Floppies
			percent	
Samson	91	96	81	80
Monroe	81	NA	65	30

Across both sites, floppies performed the poorest (table 1). Sondereggers, or seedlings classified as such, had lower survival rates than target seedlings. Some seedlings originally thought to be sondereggers turned out to be regular longleaf pine seedlings. Seedlings that were obviously sondereggers died at greater rates than did true longleaf seedlings. Doubles did better than expected on the Samson Site where 96 percent of the plugs had at least one surviving seedling.

CONCLUSIONS

- Removing floppies and sonderegger seedlings prior to planting may increase overall survival rates on some sites
- Floppies may exhibit good survival rates under optimal conditions. Conversely, poor quality seedlings may experience higher mortality under more adverse conditions
- Doubles appear to initially survive as well as target seedlings
- True sonderegger seedlings may suffer greater mortality rates than reported here since some seedlings included in hybrid plots turned out to be regular longleaf pine seedlings. Seedlings exhibiting minimal stem elongation (1 to 2 inches) in the container are often true longleaf seedlings.

ADDITIONAL STUDY

The Samson and Monroe Sites will be tracked for survival and growth for at least 2 years. In the winter of 2002–03, additional seedling quality studies were installed in Milledgeville, GA, Lexington, SC, Denton, GA, and on the Solon Dixon Forestry Education Center near Andalusia, AL. Treatments installed during the winter of 2002/03 on these subsequent sites include:

1. Target/good quality seedlings [> 6.0 mm root-collar diameter (RCD)]
2. J-rooted average (> 6.0 mm RCD)
3. Floppy small (< 4.75 mm RCD)
4. J-rooted floppy (4.75 to 7.00 mm RCD)
5. Floppy- large (4.75 to 7.00 mm RCD)
6. Co-dominant double—at least 1 seedling > 6.0 mm RCD. No more than 3.0 mm difference between seedlings)
7. Double—1 suppressed (at least 1 seedling > 6.0 mm RCD. No less than 3.0 mm difference between seedlings.)
8. Extra-large RCD (≥ 9.0 mm RCD)
9. Hybrids (Sondereggers).

SUMMARY

Visually sorting container-grown longleaf pine seedlings may result in the removal of numerous floppy, hybrid, and double seedlings. Removing floppies and sondereggers will likely result in an increased overall survival rate, especially when adverse environmental factors stress newly planted seedlings.

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Pine Plantation Silviculture

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THINNING GUIDELINES FOR LOBLOLLY PINE PLANTATIONS IN EASTERN TEXAS BASED ON ALTERNATIVE MANAGEMENT CRITERIA

Charles T. Stiff and William F. Stansfield[1]

Abstract—Separate thinning guidelines were developed for maximizing land expectation value (LEV), present net worth (PNW), and total sawlog yield (TSY) of existing and future loblolly pine (*Pinus taeda* L.) plantations in eastern Texas. The guidelines were created using data from simulated stands which were thinned one time during their rotation using a combination row (20 percent) and selection thin to achieve a residual stocking target. LEV for future stands which had been thinned indicated optimal rotation ages of 20, 24, 28, and 32 years for site index 85, 75, 65, and 55 feet, respectively. For existing stands at optimal rotation age, PNW increased with both thinning age and site index. However, for future stands at optimal rotation age, LEV reaches maximum values at thinning ages that vary by site index. TSY reached maximum values at residual stocking levels, which increased with increasing site index for both existing and future stands. Marginal analyses indicated that when thinning older stands of poorer site quality, economic criteria (PNW or LEV) increased with higher initial stocking, and total sawlog yield (TSY) decreased with lower initial stocking. Regression tree analysis used thinning age and residual stocking for predicting PNW, LEV, and TSY by initial stand attributes (site index, and initial stand age and stocking). Thinning guidelines were derived from the tree-based models. A four step procedure is provided for applying the guidelines.

INTRODUCTION

Thinning has been a commonly employed silvicultural tool for achieving landowner financial and raw material goals. Despite its wide spread application, there is still much disagreement between professional foresters and forestry organizations with respect to the efficacy, timing, and intensity of mid-rotation thinning treatments. Guidelines are needed so that thinning can be implemented in a manner consistent with a landowner's specific goals.

Various dynamic programming (DP) formulations have been utilized to determine optimal thinning guidelines and/or rotation ages for even-aged stands (Amidon and Akin 1968; Brodie and Kao 1979). Although DP has been widely advocated for determining thinning and rotation ages, implementation is difficult due to the lack of commercial DP software. In most cases, software to perform the analysis must be custom coded. Additionally, as the number of state descriptors increase, so does the magnitude of the problem, thereby increasing computer memory requirements and the time required to solve the problem.

Using DP at the stand level will provide optimal estimates of thinning prescriptions and rotation ages. However, utilization of constrained forest-wide harvest scheduling will often deviate from the DP solution. In the current study, good feasible guidelines were desired in lieu of developing an optimal solution for thinning future and existing stands. Such guidelines would provide a range of options to incorporate into the forest-wide harvest scheduling and permit field operations some flexibility to account for stand and stem quality considerations.

The objectives of this study were to utilize simulated stand data to: (1) investigate the relationship between site quality, initial stand age and stocking, thinning age and intensity, and alternative management criteria for assessing the effectiveness of thinning treatments; and (2) develop separate thinning guidelines for maximizing present net worth (PNW), land expectation value (LEV), and total sawlog yields (TSY) for existing and future loblolly pine stands on forest lands owned by Temple-Inland Forest Products Corporation in eastern Texas.

METHODS

Stand Simulator

A stand simulator was developed for predicting growth and yield in both unthinned and thinned loblolly pine plantations. User-specified inputs include: site index (average total height in feet of dominant and co-dominant loblolly pine at index age 25 years); initial stand age (Age_0 in years, minimum 3 years), stocking (TPA_0 in trees per acre), and basal area (BAA_0 in square feet per acre); thinning type (no thin, row thin, selection thin, and combination row/selection thin) and age (Age_{Thin} in years); percent row thin; post-thin stocking (TPA_{res} in trees per acre); rotation age (Age_{Rot} in years); site preparation, planting, annual management, and harvesting costs (dollars per acre); product specifications (minimum and maximum outside bark d.b.h., and minimum outside bark top diameter) for pulp, chip-n-saw, and sawlogs; and percent interest rate for discounting costs and revenues. The simulator can project growth for both future ($Age_0 = 3$ years) and existing ($Age_0 > 3$ years) loblolly pine stands.

Stand-level dominant height (feet), basal area (square feet per acre), survival (trees per acre), and diameter percentile models were fitted with East Texas Pine Plantation Research Project (ETPPRP) data. The ETPPRP, initiated in 1982 by David Lenhart at Stephen F. Austin State University, installed 256 permanent plots in 1- to15-year-old loblolly (175 plots) and slash (81 plots) pine plantations between 1982-1984. The plots have been remeasured on a 3-year cycle, with the seventh measurement cycle completed during the

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

summer of 2000. The plots received minimal site preparation (mechanical, chemical, and burning) and no mid-rotation treatments (thinning, hardwood release, and fertilization). Component growth and yield models, therefore, provide only baseline predictions with no explicit adjustments for cultural treatments. Dominant height, basal area, and survival are predicted with the stand-level models for the duration of each simulation.

Thinning model—Prior to thinning, a current stand table is generated using predicted diameter percentiles and a parameter recovery procedure for the three parameter Weibull distribution. The residual trees per acre remaining after thinning is specified, and the corresponding post-thin residual basal area (BAA_{res} in feet^2 per acre) predicted. A thinning algorithm performs preliminary row and/or selection removals, and the post-thin stand table is then adjusted so that the trees per acre and basal area per acre summed over all diameter classes equal the whole stand TPA_{res} and BAA_{res}.

The simulator predicts basal area (square feet per acre) in a thinned stand to converge on that of an unthinned counterpart stand of the same age and site index, with the same number of surviving trees per acre (Pienaar 1979, Pienaar and Rheney 1996, Pienaar and Shiver 1984). The basal area of the unthinned stand is adjusted using a locally calibrated index of suppression model, which describes the degree of suppression that existed in the thinned stand relative to the unthinned counterpart (fig. 1).

Stand table projection—A constrained least squares method is used for projecting the post-thin stand table for the remainder of the rotation (Cao and Baldwin 1999, Matney and others 1990). Individual tree models, fitted with ETPPRP data, predict the number of surviving trees in each diameter class and the diameter growth of the minimum and maximum diameter classes in the current stand table by 3-year projection period. The projected stand table is constrained each period so that the trees per acre and basal area per acre summed over all diameter classes equal the predicted whole stand basal area (feet^2 per acre) and trees per acre.

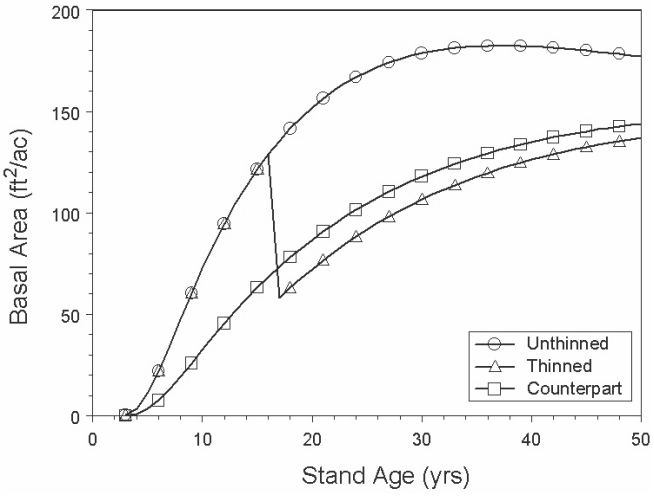

Figure 1—Predicted basal area (square feet per acre) in unthinned and thinned stands.

Economic management criteria—Pulp, chip-n-saw, and sawlog stumpage values (dollars per cord) for thinning and clear-cutting harvest operations are calculated using net converted values (NCV) and user-defined harvest costs (dollars per cord), which are adjusted for the timber source and mill destination. Thinning and clear-cutting revenues (dollars per acre), along with site preparation, planting, and management costs are appreciated to rotation age using the user-defined interest rate, and a net revenue is calculated in future dollars per acre. For future stands, a land (LEV) or soil (SEV) expectation value is calculated as the future net revenue discounted as a perpetual periodic series:

$$LEV = \frac{NR}{(1+i)^t - 1} \quad (1)$$

where, NR is the future net revenue (dollars per acre) or amount of periodic payment, "i" is the annual interest rate (percent per 100), and "t" is the rotation length (years) or interval between periodic payments; and for existing stands, a present net worth (PNW) is calculated as:

$$PNW = \frac{NR}{(1+i)^n} + \frac{LEV}{(1+i)^n} \quad (2)$$

where, "n" is the number of years until the clear-cutting harvest.

Site preparation and planting costs are included in net revenue calculations for future stands but excluded as sunk costs for existing stands.

Simulated Stand Data

The simulator generated stand attribute data for all combinations of the following input values, where Age_{Thin} was greater than Age_0: site index (55-85 by 10 foot increments); initial stand age (3 and 9-19 by 2 year increments); initial stocking (100-1000 by 100 trees per acre increments); thinning age (no thin and 10-20 by 2-year increments); post-thin residual stocking (100-300 by 25 trees per acre increments); and rotation lengths (20-36, 20-30, 20-30, and 16-30 by 2-year increments for site index values of 55, 65, 75, and 85 feet, respectively).

Stands were thinned one time during their rotation using a combination row and selection thin to achieve a residual stocking target. The row thin removed 20 percent of the standing trees from each diameter class. A selection only thin was used if the post-thin stand resulting from the row thin had less than the residual tree target.

Product merchantability specifications (table 1), site preparation costs, stand management costs, timber source, and mill destinations were held constant for all simulations. Thinning and clear-cutting harvest operations included only basic costs, with no supplements for equipment type and fuel costs. Regeneration costs included the cost of planted

Table 1—Product merchantability specifications for loblolly pine

Product	Minimum d.b.h.	Maximim d.b.h.	Minimum top diameter
	- - - - - - - - - - - -	*inches*	- - - - - - - - - - - -
Pulp	5.0	8.0	2.0
Chip-n-saw	8.0	10.0	5.0
Sawlog	10.0	—	6.0

trees (assuming 80 percent survival at age 3 years in future stands and 550 planted trees per acre in existing stands) and a graduated planting cost per acre. A constant 9 percent interest rate was used for all revenue and cost calculations.

RESULTS

The stand simulator produced response data for 52,765 (1,600 existing and future unthinned stands; 11,668 future thinned stands; and 39,497 existing thinned stands) successfully completed simulations with only a 0.2 percent unexplained failure rate.

Variance Component Analysis

All rotation ages—A variance component analysis (SPLUS 6 2001a, SPLUS 6 2001b) was used to see how much variability in the predicted management criteria (PNW, LEV, and TSY) was explained by current stand attributes (site index, Age_0, TPA_0). This preliminary analysis included data from all rotation ages.

Current stand attributes explained over 99 percent of the variability in the economic management criteria (PNW and LEV) for both existing and future stands. Site index and interaction terms with site index accounted for 96.6 and 84.5 percent of the variability in the future and existing stand data, respectively (table 2). PNW and LEV were larger for increasing site index values.

For both existing and future stand data, site index and rotation age explained approximately 55 and 40 percent of the variability in TSY, respectively. The residual error was 1.7 and 2.3 percent for existing and future stand data (table 2). TSY increased with both increasing rotation ages and site index values.

Since TSY increases with longer rotation lengths, thinning is a necessary activity to increase sawlog yield only for specified rotation ages. Rotation ages that maximize LEV by site index class are consistent with the management goals of industrial forestry landowners. LEV for future stands which had been thinned indicated optimal rotation ages of 20, 24, 28, and 32 years for site index 85, 75, 65, and 55 feet, respectively (fig. 2).

Optimal rotation ages—Simulated stand data associated with optimal rotation ages were used for subsequent analyses and for developing thinning guidelines.

Table 2—Estimated maximum likelihood variance components by management criteria and stand attributes (factors) for future and existing loblolly pine stands

Stand data		Mgmt. criteria	Percent variance explained by factor[a] Site index	Age_0	TPA_0	Age_R	Residual error
	no.		*feet*	*years*		*years*	
Future	11,668	LEV	96.6	—	1.0	0.0	0.6
		TSY	55.1	—	0.4	40.8	2.3
	1,626	LEV	98.5	—	1.1	—	0.4
		TSY	85.0	—	3.7	—	10.6
Existing	39,497	PNW[b]	74.1	14.5	0.0	0.0	0.2
		TSY	55.5	0.0	1.2	39.6	1.7
	5,513	PNW[c]	79.2	13.0	0.0	—	0.1
		TSY[d]	79.8	1.2	9.9	—	5.9

TPA = trees per acre; LEV = land expectation value; TSY = sawlog yield; PNW = present net worth.

[a] Interaction terms account for unexplained variation in each row; future and existing variance components with larger N are calculated using all rotation ages combined, while components in rows with smaller N are based on optimal rotation ages.

[b] 10.4 percent variance explained by site index x age_0.

[c] 7.6 percent variance explained by site index x age_0.

[d] 2.1percent variance explained by site index x TPA_0.

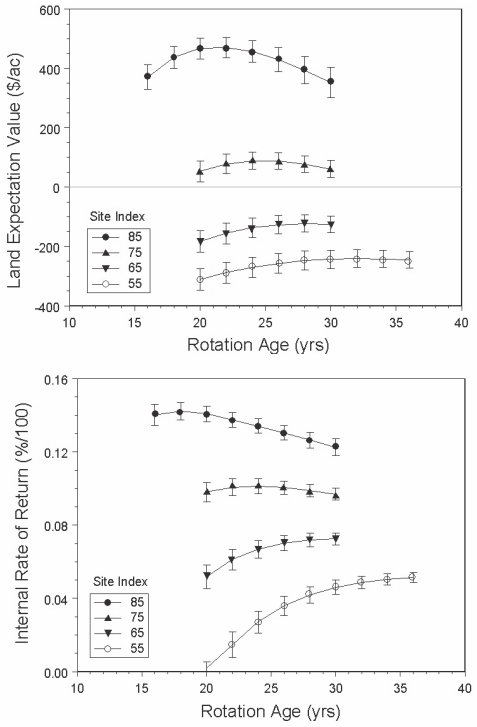

Figure 2—Mean LEV and IRR by rotation age (Age_{Rot}) and site index (feet) in future thinned stands. Error bars indicate ±1 standard deviation.

Variance components explaining the variability in PNW and LEV were similar to those calculated for all rotation ages (table 2). For both existing and future stands, however, site index and TPA_0 explained more variability in TSY, with corresponding increases in residual error. The unexplained variability (residual error) was available for developing thinning prescriptions based on thinning age and post-thin residual trees per acre.

For existing stands, PNW increases with both thinning age and site index (fig. 3). TSY also increases with site index but decreases with increasing thinning age, except for site index 85 which decreases to age 12 years and then gradually increases to age 18 years. Both PNW and TSY attain maximum values at post-thin residual stocking levels, which increase with increasing site index. Similar trends exist for future stand data, except for LEV, which reaches maximum values at thinning ages that vary by site index.

Marginal Analysis

Are there circumstances when choosing not to thin will produce greater financial (dollars per acre) and/or fiber (cords per acre) returns? That question can be quickly answered by plotting PNW, LEV, or TSY against its marginal value for both existing and future stand data. The marginal values are calculated as the difference between the no thinned and thinned management criteria values predicted for each combination of initial stand attributes (site index, Age_0, and TPA_0). If the difference is equal to or greater than zero, then do not thin. On the other hand, thinning will provide additional benefit if the difference is negative.

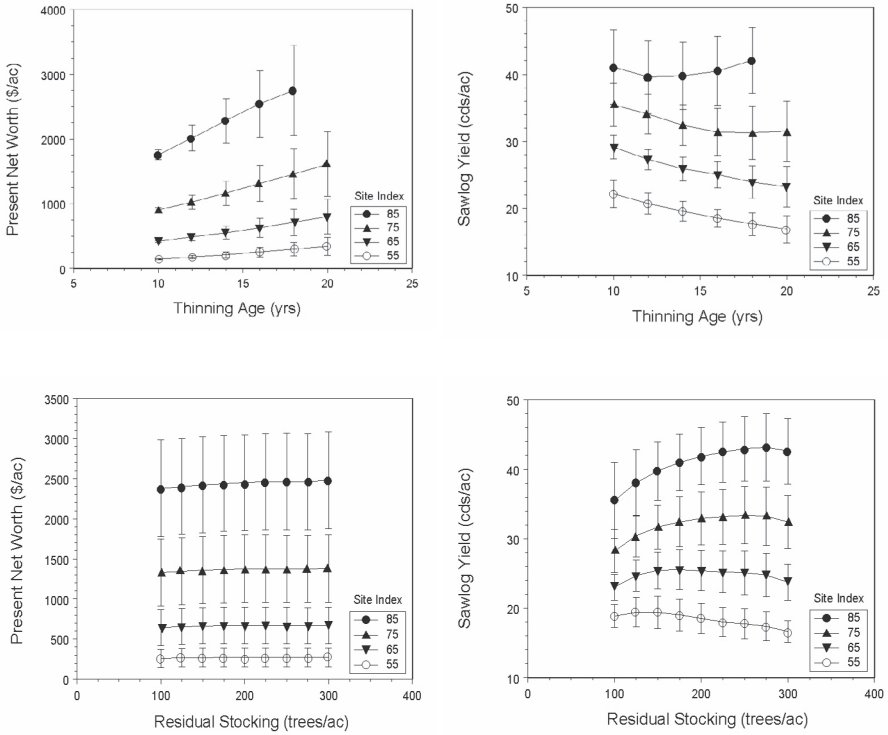

Figure 3—Mean PNW and TSY by thinning age (Age_{Thin}), residual trees per acre (TPA_{res}), and site index (feet) in existing thinned stands. Error bars indicate ±1 standard deviation.

For existing stand data, PNW and TSY were plotted against their marginal values by site index (fig. 4). The decision not to thin occurs more frequently with increasing site index for both PNW and TSY management criteria. For maximizing PNW, stands with higher site index (75 and 85 feet) have larger marginal PNW with increasing Age_0 and TPA_0; stands with lower site index (55 and 65 feet) have smaller marginal PNW. Thinning thus becomes a more viable economic treatment for older stands with poorer site quality and higher stocking. For maximizing TSY, marginal TSY increases with increasing Age_0, except for site index 85 feet, which has decreasing marginal TSY. Marginal TSY decreases with increasing TPA_0 for site index 55 feet. However, at higher site indices, TSY increases to a maximum, which occurs at progressively higher TPA_0 and then decreases. Thinning thus becomes a less viable treatment for older stands with lower initial stocking. The plotted relationships for marginal LEV and TSY are similar using future (Age_0 = 3 years) stand data.

Regression Tree Analysis

Regression tree analysis (RTA) is a method for fitting trees to predict a quantitative variable. The computer algorithm performs stepwise splitting based on a list of potential predictor variables, choosing predictor variables and their cut points that yield the smallest overall within cluster sum of squares. The fitting procedure minimizes a least squares loss function and reports the proportion of reduction in error (PRE) as a goodness-of-fit statistic (Venables and Ripley 1999).

The advantages of tree-based models include: invariance of predictor variables to monotonic transformations; the capability to handle missing values in response and predictor variables; the flexibility to handle a broad range of response types and non-normally distributed predictor variables; the ability to depict complex interactions between predictor variables; and clearer, more easily understood interpretations of nonlinear relationships and complex interactions (De'ath and Fabricius 2000).

Existing and future stand data were first assigned to strata using site index, Age_0, and TPA_0. Trees were then fitted by strata to predict PNW and TSY in existing stands and LEV and TSY in future stands (SPLUS 6 2001). Fitted trees were constrained to have no more than four terminal nodes based on a preliminary tenfold cross validation. Thinning age and post-thin residual trees per acre were used as potential predictor variables.

Figure 5 shows a fitted regression tree for predicting PNW in an existing stand which has site index = 65 feet, Age_0 = 11 years, and TPA_0 = 500 trees per acre. The PRE was 0.74, and histograms show the distribution of observed PNW values assigned to each node. The tree has four terminal nodes, with mean PNW values ranging from $526.40 per acre to $567.80 per acre. The largest mean PNW is predicted for Age_{Thin} = 20 years and TPA_{res} = 100-300 trees per acre.

Thinning Guidelines

Thinning age and post-thin residual trees per acre were used to split the data that had been stratified by current stand conditions into more homogeneous groups, giving

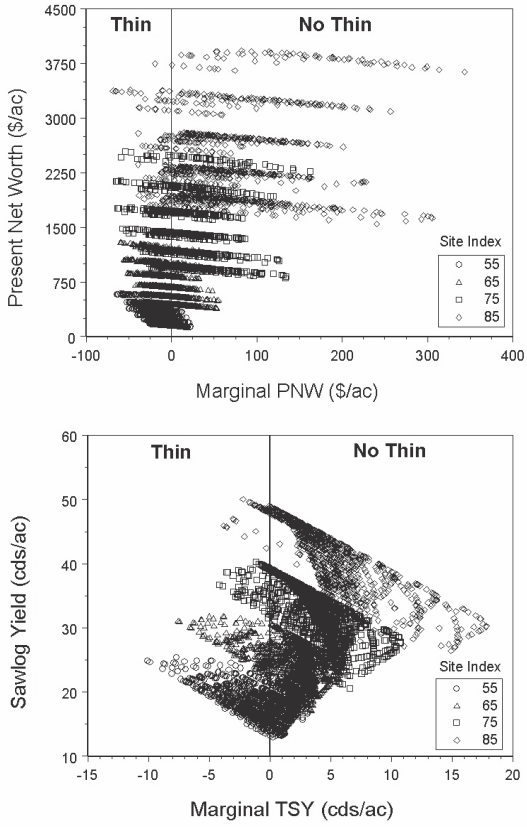

Figure 4—PNW and TSY observations versus their marginal (unthinned minus thinned) values by site index (feet) for existing thinned stands.

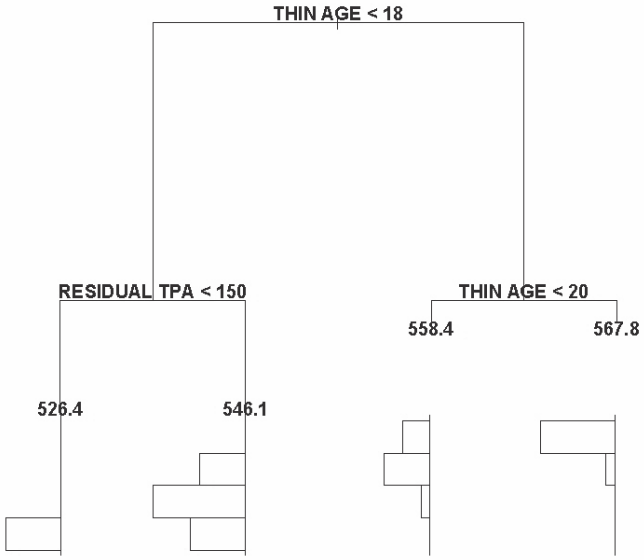

Figure 5—Fitted regression tree for predicting PNW in existing stands with site index = 65 feet, Age_0 = 11 years, and TPA_0 = 500 trees per acre. Each node is labeled with the predicted mean PNW (dollars per acre).

smaller within group and greater between group variability. The groups formed by the RTA splitting process were subsequently sorted in descending order by PNW, LEV, and TSY for future and existing stands and assigned a thinning rank or priority. Lower ranks (the highest thinning priority) were associated with current stand conditions and thinning prescriptions with either the highest mean PNW or LEV, or the largest mean TSY. Within each group there was one optimal and several sub-optimal values for each management criteria. Sub-optimal values were removed from the lists, which were then resorted in descending order and re-assigned a thinning rank. This procedure was used to create thinning guidelines by PNW and TSY for existing stands and by LEV and TSY for future stands.

Tables 3 and 4 illustrate thinning guidelines for maximizing PNW and TSY, respectively, in an existing stand. The thinning guidelines are applied using the following 4-step procedure:

Site index (feet), initial stand age (years), and initial stocking (trees per acre) are estimated using a pre-thin stand inventory (e.g., site index = 65 feet, Age_0 = 11 years, and TPA_0 = 600 trees per acre). The appropriate guideline is accessed using the estimated stand attributes. A thinning prescription (Age_{thin} and TPA_{res}) is given, along with the mean and standard deviation of the predicted management criteria (PNW or TSY). In addition, the guideline lists the predicted value of the management criteria for a no-thin scenario. For example: The thinning prescription for maximizing PNW using table 3 is Age_{thin} = 18-20 years and TPA_{res} = 175-300 trees per acre with a predicted PNW of $571.70 ± $4.97 per acre and a no-thin PNW of $553.74 per acre. The thinning prescription for maximizing TSY using table 4 is Age_{thin} = 12-13 years and TPA_{res} = 100-300 trees per acre with a predicted mean TSY of 27.89 ± 1.54 cords per acre and a no-thin TSY of 27.82 cords per acre.

These prescriptions provide a recommended range of thinning ages and post-thin residual stocking, which would give good feasible solutions requiring professional judgment for field application.

The stand simulator uses the recommended prescription to search for a thinning age and post-thin residual stocking

Table 3—Thinning guidelines for maximizing PNW in an existing stand with site index = 65 feet, Age_0 = 11 years, and Age_{Rot} = 28 years

Existing stand	Thinning prescription		Thin PNW		No thin
TPA_0	Thin age	TPA_{res}	Mean	Std. dev.	PNW
	years		*- - - - - dollars per acre - - - - -*		
250 – 349	18 – 20	100 – 200	552.58	6.66	542.21
350 – 449	18 – 20	100 – 300	557.58	8.64	550.09
450 – 549	20	100 – 300	567.77	8.42	553.62
550 – 649	18 – 20	175 – 300	571.70	4.97	553.74
650 – 749	18 – 20	175 – 300	575.24	3.94	551.24
750 – 849	14 – 20	150 – 300	564.76	4.50	548.87
850 – 949	16 – 20	150 – 300	562.97	4.17	545.79
950 – 1,049	14 – 20	150 – 300	564.47	5.27	542.34

TPA = trees per acre; PNW = present net worth.

Table 4—Thinning guidelines for maximizing TSY in an existing stand with site index = 65 feet, Age_0 = 11 years, and Age_{Rot} = 28 years

Existing stand	Thinning prescription		Thin sawlog yield		No thin
TPA_0	Thin age	TPA_{res}	Mean	Std. dev.	Sawlog
	years		*- - - - cords per acre - - - -*		
250 – 349	12 – 20	250 – 300	30.07	0.19	30.66
350 – 449	12 – 20	150 – 300	27.30	0.54	29.96
450 – 549	12 – 17	125 – 250	27.10	0.52	28.96
550 – 649	12 – 13	100 – 300	27.89	1.54	27.82
650 – 749	12 – 13	100 – 300	27.49	1.57	26.60
750 – 849	12 – 13	100 – 300	26.99	1.50	25.43
850 – 949	12 – 13	100 – 300	26.49	1.43	24.30
950 – 1,049	12 – 13	100 – 300	26.54	1.70	23.21

TSY = sawlog yield; TPA = trees per acre.

with maximum values for the management criteria (PNW or TSY). For example,

- For maximizing PNW, Age_{thin} = 18 years and TPA_{res} = 225 trees per acre with a predicted PNW of $581.56 per acre.
- For maximizing TSY, Age_{thin} = 12 years and TPA_{res} = 200 trees per acre with a predicted TSY of 29.48 cords per acre.

If the predicted value for the management criteria (PNW or TSY) is greater than the no thin value, then thin the stand; otherwise, do not thin the stand. The existing stand in the example would be thinned using both the PNW and TSY management criteria.

DISCUSSION AND CONCLUSION

Different landowner objectives require different thinning regimes. In this analysis we examined the timing and intensity of a single entry thinning utilizing an optimal rotation age. The subsequent guidelines provide direction to field and planning personnel for planning and implementing two common landowner objectives. As suggested by the thinning guidelines, maximization of TSY requires early thinning when compared to maximization of PNW or LEV. Maximization of PNW is relatively insensitive to the residual stocking levels (fig. 3). In contrast, if maximizing TSY is the management goal, lower residual stocking should be the target with decreasing site index. However, individual stands will deviate from these trends based on initial stand attributes.

Despite landowner objectives, innate site productivity is the most important predictor for financial and raw material production. In general, there exists greater opportunity to increase PNW, LEV, and TSY by preferentially thinning lower site quality stands. Higher site quality lands provide less opportunity for thinning, as opportunity costs exist for reduced stocking.

Thinning guidelines were developed using regression tree analysis. This methodology provided an efficient means of summarizing data and identified feasible regions of thinning intensities and ages for maximizing a particular landowner objective. The regions identified with regression tree analysis provide field personnel with flexibility for determining residual trees per acre. This flexibility can be utilized to address stand specific stem quality considerations when selecting leave trees. Similarly, the feasible regions provide a range of thinning ages, which give wider latitude for achieving operational thinning constraints such as minimum stem length. The flexibility can also be beneficial in developing good and feasible thinning regimes for constrained harvest scheduling that are aligned with the objective function of the planning problem. Finally, if additional analysis is desired to determine the optimal thinning age and residual trees per acre, the thinning guidelines can define the boundaries of the search, thus reducing the time required to identify the optimal solutions.

ACKNOWLEDGMENTS

The authors gratefully acknowledge David Lenhart and Dean Coble, ETPPRP at Stephen F. Austin University, for providing remeasurement data to develop stand growth and yield models; Quang Cao, Louisiana State University, for developing individual tree growth models used in stand table projection; and Temple-Inland Forest Products Corporation district foresters in Texas and Louisiana for data collection.

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OUSTAR: A PREMIXED BLEND OF VELPAR DF+OUST XP FOR HERBACEOUS WEED CONTROL AND ENHANCED LOBLOLLY PINE SEEDLING PERFORMANCE

Jimmie L. Yeiser and Andrew W. Ezell[1]

Abstract—Six tests were established comparing the herbaceous weed control (HWC) and resultant loblolly pine (*Pinus taeda* L.) seedling performance from treatments of Oustar (0, 10, 13, 16, 19 ounces product acre^{-1}), and industry standards (Velpar L+Oust 32+2; Arsenal+Oust 4+2 both in ounces product acre^{-1}). Sites were prepared prior to planting with: burn only, chemical only, mechanical only, or mechanical and chemical methods. Oustar (13 ounces) and industry standards provided similar weed control and seedling performance. The low rate (10 ounces) of Oustar applied to sandy loam soils receiving chemical preparation and plowing prior to planting provided bareground comparable to industry standards. When averaged across test sites, herbicide plots consistently had more bareground than untreated plots by nearly 2x 30 days after treatment (DAT), 3x 60 DAT, 4x 90 DAT, and 5x 120 DAT. Similarly, herbicide plots had more seedling survival (9 percent), total height (0.69 feet), ground line diameter (0.26 inch), and volume index (1.54 cubic feet) than untreated plots.

INTRODUCTION

Herbaceous weeds compete with newly planted loblolly pine (*Pinus taeda* L.) seedlings for water, nutrients, light, and space. Forest managers seeking enhanced survival and seedling growth practice herbaceous weed control (HWC) at planting. Velpar L (liquid) and Oust (dry) are forest herbicides manufactured by E.I. du Pont de Nemours and Company. These products are packaged separately but commonly mixed together in a spray tank to control herbaceous weeds of newly planted pine seedlings. Users must buy, store, and handle both products separately before mixing them on application day. Each gallon of Velpar L contains 25 percent of the active ingredient, hexazinone, plus alcohol and other ingredients for stability and shelf life. The alcohol makes Velpar L more flammable than other forest herbicides. Oust herbicide is a granule containing 75 percent sulfometuron, the active ingredient. The product is pan granulated with chemical binders that hold the dust-like particles together. Oust forms a suspension when added to water. If allowed to sit, particles of Oust settle to the tank bottom. There, the same binders used to hold the dry particles together turn the Oust-particles into a paste. Good agitation prior to spraying moves Oust from the tank bottom and into suspension.

New extruded granular formulations of Oust and Velpar were tested in 1999. Extruded granules lack the chemical binders previously used for pan granules. Consequently, the new formulation, called Oust XP, has improved solubility. If allowed to settle, new Oust XP requires less agitation for resuspension. The new formulation of Velpar L, called Velpar DF, is alcohol-free and 75 percent concentrated. Furthermore, the new granules of Oust XP and Velpar DF are identical in size, shape, and density.

Oustar, developed for testing in 2000, is a premixed blend of Oust XP and Velpar DF. It brings the enhanced properties of the new formulations into one container for increased convenience of storage, handling, and mixing. The objective of this project was to compare Oustar and conventional industry standards (Velpar L+Oust; Arsenal+Oust) for HWC and loblolly pine seedling performance.

METHODS

Field trials were established in March 2000 at six sites: in Diboll and Lufkin, TX; Whitfield, AL; Picayune, MS; Cold Point, SC; and Starkville, MS. The sites were varied in their preparation intensity (table 1). Herbicide treatments were applied pre-emergence at Picayune, Diboll, Cold Point, and Starkville and postemergence at Lufkin and Whitfield. Herbicide treatments were: (1) Oustar 10 ounce, (2) Oustar 13 ounces, (3) Oustar 16 ounces, (4) Oustar 19 ounces, (5) Velpar L+Oust XP 32+2 ounces, (6) Arsenal AC+Oust XP 4+2 ounces, and (7) untreated check. All rates were applied in ounces of product per treated acre.

Treatment plots in Starkville, Diboll, and Lufkin contained 16 seedlings in a single row. Measurement plots were inside treatment plots and contained 12 seedlings with 2 buffer seedlings on each end. In Whitfield, Cold Point, and Picayune, treatment and measurement plots contained 10 seedlings.

Treatments were visually evaluated for percent bareground at 30, 60, 90, and 120 days after treatment (DAT). Seedlings were assessed for survival (percent) and measured for height (HT, in feet), and ground line diameter (GLD, in inches) prior to treatment and after one and two growing seasons. Volume index (VI) was computed as VI = HT X GLD^2 and expressed in cubic feet. Year-1 cover and year-2 growth are presented here.

All test sites had four blocks each. Treatments were assigned to a randomized complete block design. Treatment effects were partitioned using the analysis of variance with means separated using Duncan's New Multiple Range Test ($P \leq 0.05$).

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Table 1—A summarized description of test sites

Site	Picayune, MS	Diboll, TX	Lufkin, TX
Established	2000	2000	2000
Physiography	Flatwoods LCP	Hilly UCP	Hilly UCP
Soil	Silt loam pH 4.2	Sandy loam pH 5.4	Sandy loam pH 5.0
Harvested	Dec 98	Sep 98	May 99
Site Prep1	Oct 99 Shear, rake Windrow	Sep 99 Arsenal + Garlon 4 16 oz + 2 qt	Aug 99 Wildfire —
Site Prep2	Dec 99 Burned windrows Planted Jan 00 Bare root, hand	Oct 99 Combination plow Jan 00 Container, hand	— — Jan 00 Bare root, hand
Treated Percent Cover	5 Apr 00 < 1 percent @ 6" Pre-emergence	14 Apr 00 < 1 percent @ 6" Pre-emergence	15 Apr 00 < 40 percent @ 6" Post-emergence
Treatments Total volume	5-foot band 10 GPA	5-foot band 10 GPA	5-foot band 10 GPA
Major Forbs	*Eupatorium spp* *Rubus spp*	*Eupatoriium spp* *Erechtites spp* *Croton spp*	*Eupatorium spp* *Conyza spp*
Major grasses	*Panicum spp*	—	*Panicum spp* Dicanthelium spp *Andropogon spp*

Site	Cold Point, SC	Whitfield, AL	Starkville, MS
Established	2000	2000	2000
Physiography	Piedmont	Interior flatwood LCP	Hilly UCP
Soil	Sandy loam pH 5.4	Sandy loam pH 4.2	Sandy clay loam pH 5.2
Harvested	Jul 98	Dec 98	May 99
Site Prep1	May 99 Chopper + oil 48 oz + 5 qt	Jul 99 Shear, rake windrow —	Aug 99 Chopper+Accord SP 48 oz + 4qt
Site Prep2	Dec 99 Combination plow	— —	Oct99 Burned
Planted	Jan 00 Bare root, hand	Jan 00 Bare root, machine	Jan 00 Bare root, hand
Treated Total Volume Percent Cover	13 Apr 00 10 GPA < 10 percent @ 6" Pre-emergence	6 Apr 00 10 GPA < 80 percent @ 12" Post-emergence	10 Apr 00 10 GPA < 10 percent @ 6" Pre-emergence
Treatments	5-foot band	5-foot band	5-foot band
Major Forbs	*Ambrosia spp* *Rubus spp*	*Eupatorium spp* *Erechtites spp* *Ambrosia* spp	*Eupatorium spp* *Conyza spp*
Major Grasses	*Panicum spp* *Dicantheium* spp *Andropogon* spp	*Panicum spp* *Dicanthelium* spp	*Panicum spp* *Dicanthelium* spp *Andropogon* spp

LCP=lower coastal plain; UCP=upper coastal plain

RESULTS

Mean Bareground

Bareground values were averaged across all six sites and presented in table 2 for each evaluation date. At 30 DAT, all herbicide test treatments were similarly weed free. At 60 DAT, bareground on plots receiving 10 ounces of Oustar was less than the weed-free value for higher Oustar rates but similar to industry standards. At 90 DAT, herbicide treatments provided very similar weed control, with differences detected among the highest (84 percent) and lowest (76 percent) levels of bareground. At 120 DAT, bareground was similar for all herbicide treatments.

Table 2—Mean bareground (percent) 30 through 120 days after treatment (DAT) with Oustar and industry standards (Velpar L+Oust XP (V+O); Arsenal+Oust XP (A+O)) for herbaceous weed control at six sites

Site	Oustar				V+O	A+O		Site by	Site
DAT	10	13	16	19	32+2[a]	4+2[a]	Check	DAT mean[b]	mean[c]
Overall Mean									
30	91a[d]	94a	95a	96a	93a	91a	46b		
60	84b	90a	92a	90a	89ab	88ab	32c		
90	76b	81ab	84a	80ab	81ab	79ab	22c		
120	61a	65a	65a	69a	67a	66a	12b		
Cold Point, SC									69bc
30	85a	89a	91a	94a	82a	86a	65b	85bc	
60	81a	87a	83a	85a	77a	87a	44b	78c	
90	76a	67a	65a	73a	64a	62a	31b	62b	
120	53a	48ab	55a	66a	48ab	48ab	26b	49b	
Diboll, TX									86a
30	93a	99a	99a	100a	99a	99a	28b	88b	
60	94a	97a	98a	99a	97a	99a	28b	87b	
90	90a	96a	96a	99a	97a	99a	28b	86a	
120	92a	92a	72a	99a	97a	96a	18b	81a	
Lufkin, TX									71b
30	93a	99a	99a	100a	99a	99a	13b	86bc	
60	78b	85b	93a	94a	85b	84b	6d	75c	
90	68c	75b	83a	84a	75b	74b	2d	66b	
120	53c	60b	71a	74a	64b	60b	2d	55b	
Picayune, MS									89a
30	95ab	98a	97a	99a	98a	99a	92b	97a	
60	92a	96a	96a	96a	98a	97a	75b	93a	
90	90a	96a	95a	97a	98a	95a	51b	89a	
120	75b	89ab	95a	94a	92a	84ab	12c	77a	
Starkville, MS									68bc
30	92a	90a	91a	90a	91a	93a	37b	84bc	
60	87a	86a	87a	84a	89a	83a	17b	76c	
90	70ab	57b	68ab	67ab	75ab	80a	5c	60b	
120	63ab	48b	62ab	52b	62ab	68a	5c	51b	
Whitfield, AL									64c
30	88ab	88ab	93a	95a	91a	73b	41c	81c	
60	73c	91ab	97a	81bc	91ab	79bc	18d	76c	
90	59c	89ab	96a	60c	77abc	68bc	14d	66b	
120	29b	47a	38ab	29b	39ab	38ab	9c	32c	

[a] Ounces of product per acre.
[b] DAT means within a column sharing the same letter are not significantly different (Duncan's New Multiple Range Test ($P \leq 0.05$).
[c] Site means within a column sharing the same letter are not significantly different (Duncan's New Multiple Range Test ($P \leq 0.05$).
[d] Treatment means within a row sharing the same letter are not significantly different (Duncan's New Multiple Range Test ($P \leq 0.05$).

As the growing season progressed, the values for bareground showed little range variation between Oustar use rate and industry standards (table 2). For example, bareground at 30 DAT ranged only 5 percent, from a low of 91 to a high of 96 percent for Oustar treatments; at 60 DAT, the range was 8 percent from 84 to 92 percent; at 90 DAT, the range was 8 percent from 76 to 84 percent; and at 120 DAT, the range was 8 percent from 61 to 69 percent. For all evaluation dates, industry standards consistently provided weed-free growing space intermediate between the low and high Oustar test rates.

Herbicide treatments consistently exhibited more weed-free growing space than that observed on untreated checks (table 2). The mean bareground of all herbaceous weed treatments compared with the untreated check was nearly 2x 30 DAT, 3x 60 DAT, 4x 90 DAT, and 5x 120 DAT.

Bareground by Site

Mean percent bareground varied by site (table 2). Weed-free conditions were highest and similar at Picayune (89 percent) and Diboll (86 percent). Bareground at Lufkin (71 percent) was intermediate and similar to that at Cold Point (69 percent) and Starkville (68 percent). Bareground was lowest at Whitfield (64 percent) but similar to that at Cold Point and Starkville. For all evaluations, sites averaged at least 64 percent weed-free.

The site by DAT means show the speed with which herbicide treatments provided bareground (table 2). For example, at 60 DAT, percent bareground was statistically Picayune> Diboll>Lufkin=Cold Point=Starkville=Whitfield and numerically 93, 87, 75, 78, 76, and 76 percent, respectively. At 120 days, bareground was statistically Diboll=Picayune> Lufkin=Starkville=Cold Point>Whitfield and numerically 81, 77, 55, 51, 49, and 32 percent, respectively. Picayune and Diboll sites on application day had the lowest ground cover at less than one percent. Whitfield on application day had the highest ground cover at almost 80 percent. Sites with less ground cover on application day exhibited more bareground at 60 and 120DAT and generally at all evaluations than sites with high levels of cover.

The sites by DAT means illustrate the duration of weed control (table 2). For example, at Cold Point, bareground peaked 30 DAT (85 percent) and was lowest 120 DAT at 49 percent, a decline of 36 percent. During this same period, Diboll was 88 and 81 percent, Lufkin was 86 and 55 percent, Picayune was 97 and 77 percent, Starkville was 84 and 51 percent, and Whitfield was 81 and 32 percent, respectively.

The sites by herbicide by DAT means show high rates of Oustar (16 ounces, 19 ounces) provided best and similar weed control across all sites (table 2). Weed control among use rates of Oustar and industry standards was similar at Cold Point, Diboll, and Picayune (table 2). For example, at Cold Point 30 DAT, Oustar treatments, industry standards, and all herbicide treatments averaged 90, 84, and 88 percent bareground, respectively; at 60 DAT, the averages were 84, 82, and 83 percent; at 90 DAT, the averages were 70, 63, and 68 percent; and at 120 DAT, the averages were 56, 48, and 53 percent. These data illustrate the potential contribution of quality and timely site preparation to stage of weed development on application day and the performance of Oustar and industry standards. For example, October mechanical site preparation (Picayune) and chemical followed by mechanical site preparation (Diboll and Cold Point) yielded modest herbaceous weed levels (highest at Cold Point: 90 percent bareground and < 10 percent cover 6 inches tall) readily controlled by herbicides. This gives managers HWC options during tight budgets.

Unexpected patterns in herbicide performance at Lufkin, Starkville, and Whitfield may be explained by site preparation method, timing of the method, and species composition of weed recolonization. For example, Lufkin was prepared by a wildfire. Only high rates of Oustar (16 ounces, 19 ounces) sustained best weed control through 120 DAT. Low rates of Oustar and industry standards performed well early but gradually succumbed to weed pressure. This was the only test site where industry standards were not among the best treatments tested. At Starkville, plots treated with Oustar 13 ounces were coincidentally colonized by blue vervain (*Verbena brasiliensis* Vell.), to a greater extent than plots treated with other herbicides. Blue vervain is tolerant of hexazinone and sulfometuron, the active ingredients in Oustar. Managers have little influence on seed in the soil or that blowing in following herbicide application and subsequently colonizing treatment areas. At Whitfield, mechanical preparation in July left plenty of time for autumn weed seed dissemination of plots. This was evident on application day, when weeds nearly 1foot tall occupied approximately 80 percent of the site. Heavy weed development on application day was followed by the most aggressive weed re-colonization of all plots at all sites 120 DAT. The Lufkin and Whitfield sites illustrate the need for quality and timely site preparation prior to planting.

Bareground by Site Preparation Method

When sites were analyzed for bareground by site preparation method, HWC was similar 30 DAT for the mechanical (mech), chemical+mechanical (c+m), wildfire, or chemical methods (table 3). At 60 and 90DAT, HWC was similar and better for sites mech (Picayune and Whitfield) and c+m prepared (Cold Point and Diboll Cold Point). Similar and lowest HWC resulted from the wildfire (Lufkin) and chemical (Starkville) site preparations. At 120 DAT, the c+m prepared sites had more HWC than the site prepared only with herbicides (Starkville).

Bareground was averaged across evaluation dates to produce means for the entire growing season (table 3). Bareground following a wildfire (Lufkin) was statistically similar but numerically less than for mech (Picayune and Whitfield) and c+m (Cold Point and Diboll) prepared sites. Furthermore, bareground following a wildfire was statistically similar and numerically greater than for the chemically prepared site (Starkville). Data illustrate herbicide treatments were well suited for weed conditions following a variety of site preparation methods providing at least 68 percent bareground for the evaluation period at all sites.

Table 3—Mean bareground (percent) for site preparation methods

		Days after treatment				
Site	Site preparation	30	60	90	120	Overall
Picayune, MS Whitfield, AL	Shear, rake, windrow & burn Shear, rake, windrow	89a[a]	84a	77a	55ab	76a
Cold Point, SC Diboll, TX	Chopper + plow Arsenal + Garlon + plow	86a	82a	74a	65a	77a
Lufkin, TX	Wildfire	86a	75b	60b	55ab	70ab
Starkville, MS	Chopper + Accord SP & burn	84a	76b	66b	51b	68b

[a] Treatment means within a column sharing the same letter are not significantly different (Duncan's New Multiple Range test, $P \leq 0.05$ level).

Seedling Performance

Seedling performance after two growing seasons was averaged across all six sites. HWC increased survival (7.2 percent), total HT (0.47 foot), GLD (0.22 inch), and VI (1.22 cubic feet) above that of untreated checks. In a three-way comparison of seedlings treated with Oustar, industry standards, or nothing (untreated checks), seedling performance was similar for Oustar treatments and industry standards and both significantly better than untreated checks. For example, for the three-way comparison, survival was 85.4, 87.1, and 78.7 percent; total HT was 5.1, 5.4, and 4.7 feet; GLD 1.41, 1.48, and 1.21 inches; and VI 5.48, 6.16, and 4.48 cubic feet, respectively.

Seedling performance varied by site (table 4). Survival was, statistically, Picayune=Whitfield=Diboll>Starkville> Cold Point>Lufkin and numerically 99, 98, 97, 85, 73, and 66 percent, respectively. For total HT, statistically, Whitfield>Picayune> Starkville>Diboll>Lufkin>Cold Point and numerically 6.8, 6.4, 5.5, 4.9, 4.2, and 2.3 feet, respectively. For GLD, statistically, Picayune>Whitfield= Diboll>Lufkin>Starkville>Cold Point and numerically 1.76, 1.65, 1.58, 1.35, 1.26, and 0.51 inches, respectively. For VI, statistically, Whitfield=Picayune>Diboll=Starkville> Lufkin>Cold Point and numerically, 8.12, 8.03, 5.79, 5.26, and 0.93 cubic feet, respectively.

Table 4—Seedling survival (percent), total height (feet), ground line diameter (GLD, inches), and volume index (VI, cubic feet) two growing seasons following treatment at six sites with Oustar or industry standards (Velpar L+Oust XP (V+O); Arsenal+Oust XP (A+O)

Site	Oustar					V+O	A+O	Site
Parameter	10	13	16	19	32+2[a]	4+2[a]	Check	Mean
Overall Means								
Survival[b]	86.8a	84.5ab	85.0ab	85.4ab	85.4ab	88.7a	78.7b	
Total Height[b]	5.0bc	4.9cd	5.2ab	5.1bc	5.5a	5.3ab	4.7d	
GLD[b]	1.33d	1.39cd	1.51a	1.40bcd	1.47abc	1.49ab	1.21e	
VI ($x10^{-2}$) [b]	5.11b	5.15b	6.06a	5.59ab	6.20a	6.11a	4.48c	
Cold Point, SC								
Survival	87.5a	75.0a	62.5a	83.3a	66.7a	70.8a	61.1a	72.8c[c]
Total Height	2.8a	2.6ab	2.3ab	1.7c	2.4ab	2.2bc	2.2b	2.3f
GLD	0.58a	0.58a	0.48a	0.31b	0.52a	0.52a	0.55a	0.51e
VI ($x10^{-2}$)	1.24a	1.18a	0.83ab	0.37b	1.0a	0.92a	1.0a	0 .93d
Diboll, TX								
Survival	97.9a	97.9a	97.9a	93.8a	93.8a	100.0a	95.8a	96.7a[c]
Total Height	4.7b	4.7b	5.1ab	4.8ab	5.4a	4.8b	5.1ab	4.9d
GLD	1.45c	1.60abc	1.67ab	1.58abc	1.73a	1.53abc	1.48bc	1.58b
VI ($x10^{-2}$)	5.11b	5.44b	6.19ab	5.71b	6.90a	5.70b	5.52b	5.79b
Lufkin, TX								
Survival	64.6a	75.0a	70.8a	66.7a	66.7a	70.8a	43.8b	65.5d[c]
Total Height	4.0a	4.3a	4.4a	4.6a	4.4a	4.3a	3.0b	4.2e
GLD	1.24bc	1.37ab	1.44ab	1.45a	1.36ab	1.38ab	1.12c	1.35c
VI ($x10^{-2}$)	3.58b	4.26ab	4.54ab	4.84a	4.46ab	4.53ab	2.42c	4.19c
Picayune, MS								
Survival	100.0a	100.0a	100.0a	100.0a	100.0a	100.0a	91.7b	98.8a[c]
Total Height	6.2ab	5.6b	6.4a	6.5a	6.9a	6.6a	6.5a	6.4b
GLD	1.63c	1.65bc	1.85ab	1.77abc	1.82abc	1.94a	1.68bc	1.76a
VI ($x10^{-2}$)	7.24bc	6.56c	8.44ab	8.13abc	9.01a	8.95a	7.91abc	8.03a
Starkville, MS								
Survival	86.7ab	71.1b	84.4ab	82.2b	91.1a	93.3a	86.7ab	85.1b[c]
Total Height	5.9abc	5.2d	5.5bcd	5.3cd	6.1ab	6.3a	4.0e	5.5c
GLD	1.31bc	1.17c	1.38ab	1.28cb	1.31bc	1.56a	0.79d	1.26d
VI ($x10^{-2}$)	5.71b	4.56b	5.65b	5.15b	5.82b	7.19a	2.36c	5.26b
Whitfield, AL								
Survival	95.8a	95.8a	95.8a	100.0a	100.0a	100.0a	100.0a	98.2a[c]
Total Height	6.5ab	6.7ab	7.2a	7.3a	6.9ab	6.6ab	6.1b	6.8a
GLD	1.61a	1.63a	1.83a	1.74a	1.72a	1.68a	1.33b	1.65b
VI ($x10^{-2}$)	7.44bc	8.10ab	9.61a	8.85ab	8.61ab	8.15ab	6.14c	8.12a

[a] Ounces of product per acre.

[b] Treatment means within a row sharing the same letter are not significantly different (Duncan's New Multiple Range Test ($P \leq 0.05$).

[c] Site means for each seedling parameter within a column sharing the same letter are not significantly different (Duncan's New Multiple Range Test ($P \leq 0.05$).

Herbicide treatments commonly enhanced seedling survival and growth over untreated checks. In a comparison of treated versus untreated, performance was significantly enhanced for survival at Lufkin, Picayune, Starkville, and overall; total HT at Lufkin, Starkville, Whitfield, and overall; GLD at Diboll, Lufkin, Picayune, Starkville, Whitfield and overall; and VI at Diboll, Lufkin, Picayune, Starkville, Whitfield, and overall.

In a comparison of Velpar L+Oust (32+2 ounces) and Oustar (13 ounces) formulations, Velpar L+Oust enhanced total HT at Diboll and Picayune; and VI at Diboll and Picayune. GLD was similar at all sites. In a comparison of Arsenal (4+2ounces) and Oustar (13ounces), Arsenal+Oust enhanced total HT, GLD, and VI at Picayune. Starkville was not included in these analyses because of the invasion of blue vervain in the Oustar (13 ounces) treatment only.

As the rate of Oustar increased, GLD decreased at Cold Point and Diboll (table 5). Significant linear and negative quadratic estimates were detected at both sites and illustrate the risk of high application rates on plowed, sandy loam soils with inadequate rainfall for bed settlement.

In conclusion, weed control and seedling performance were very similar for several rates of Oustar. When compared to industry standards, comparable rates of Oustar provided similar weed control, seedling survival, and growth. Results show the potential of Oustar for safe HWC and enhanced loblolly pine seedling performance.

Table 5—Age two regression relationships for Oustar rate (10, 13, 16, 19 ounces product per acre) and ground line diameter resulting from post-plant herbaceous weed treatments on chemically prepared and plowed sandy loam soils with inadequate rainfall for good early bed settlement

	Cold Point			Diboll		
	Intercept b_0	Linear b_1	Quadratic b_2	Intercept b_0	Linear b_1	Quadratic b_2
Coefficient	-0.0267	0.1086	-0.0048	0.0198	0.2096	-0.0667
Coefficient Pr > F		0.1560	0.0703		0.0528	0.0717
Model Pr > F			0.0001			0.0596

IDENTIFYING LOBLOLLY PINE AND FOUR COMMON COMPETING HARDWOOD SPECIES USING MULTISPECTRAL REFLECTANCE ANALYSIS

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Abstract—Multispectral reflectance data were collected in midrotation loblolly pine plantations during spring, summer, and fall seasons with a hand-held spectroradiometer. All data were analyzed by discriminant analysis. Analyses resulted in species classifications with accuracies of 83 percent during the spring season, 54 percent during summer, and 82 percent during fall. Loblolly pine was correctly identified 100 percent of the time using the spring data. Multispectral remote sensing appears valuable in determining the level of hardwood competition within midrotation pine plantations and for separating pine from nonpine competitors.

INTRODUCTION

The art and science of forest management starts with field measurement. No forest, regardless of size or location, can be properly managed without a thorough knowledge of the forest conditions on site. Based on site assessment, silvicultural prescriptions can be formulated. Throughout the life or "rotation" of a forest stand, many problems may arise. Some result in detrimental effects on the growth and productivity of the stand. These include, but are not limited to, insect, fungal, bacterial, mammalian, and avian influences. The presence of other botanical species on the site can greatly influence pine growth as well. In most forest stands, noncrop species form a competitive relationship with the desired crop species; all compete for space, water, nutrients, and light.

BACKGROUND

The effects of competition on pine growth have been well researched. Control of hardwoods in young loblolly pine (*Pinus taeda* L.) stands is a management option that has resulted in good pine growth responses (Fortson and others 1996, Quicke and others 1996, Zutter and others 1988). Not only is the response to competition control at an early plantation age positive, but removal of competition at midrotation has proven to be beneficial as well. Investigators found that in treated plots within a 14-year-old pine plantation, basal area and volume of pine increased 11 percent and 20 percent, respectively, over all treatments compared to nontreated controls (Fortson and others 1996). Quicke (2001) also found that competition control in a 14-year-old pine plantation positively influenced pine growth. Six years after treatment, pine growth was 20 percent greater in treated plots than in control plots, yielding an additional ½ cord per acre per year.

Economic benefits of competition control—There are positive economic returns to midrotation hardwood control in pine plantations. Kline and Kidd (1986) estimated that under conservative economic assumptions, a 10-percent reduction in hardwood basal area yielded an average of $105 per acre increase in the net present value of a loblolly pine plantation. This estimate was based on a stand with a site index of 69 feet at base age 25 and grown through a 30-year rotation age. One study found that investment in midrotation hardwood control returned 8 percent to 14 percent annually over the remaining life of a rotation (Caulfield and others 1999). This study evaluated the returns to investment in herbicide application costs based on differing levels of control success and varying prices of pine products but did not include the costs of the competition control need assessment.

The competition assay—Assessment of competing vegetation within a pine plantation currently requires on-site measurement. As with most measurements conducted for silvicultural assessments, this often requires plots be established and physical measurements taken. Although per acre costs for such labor-intensive measurements decline as acreage increases, it remains a notable expense. Some classification systems have been outlined that require fewer measurements but include ocular estimates of competitive factors (Zutter and others 1984). The problem with these methods is the introduction of some degree of subjectivity because the systems are ocular rather than measured quantitative methods. However, the advantage of these methods is the ability to characterize species of competing woody vegetation.

Remote Sensing as a Means to Assess Competition

In order to reduce labor costs from on-site visits, other means to assess competitive conditions must be found. One promising way to make this determination with very limited *in situ* visitation is through the use of remote sensing and analysis. To effectively assess competition within a pine plantation, some means must be found to separate competitive species from the pine crop on the remotely acquired image.

Species' spectral responses—Separation of spectral responses has been a problem confronted by many investi-

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

gators. From the beginning of multispectral remote sensing, scientists have investigated many variables that influence spectral signatures. These variables range from the chemical properties of the plant to environmental stresses experienced by the tree. Spectral signatures can vary simply based on the position individual leaves occupy on the tree. Atkinson and others (1997) found that leaf samples from two species of European birch taken from stump and basal sprouts were dissimilar in spectral response to samples taken from the lower crown. Other research found that concentrations of chlorophyll determine spectral response in the electromagnetic wavelengths between 400 and 700 nm (Gitelson and others 1996, Tucker and Garrett 1977). Stress factors (Westman and Price 1987), foliage age and position in the canopy (Atkinson and others 1997, Danson 1995, Gausman 1985), nitrogen and lignin concentrations (Martin and others 1998), and other variables can cause variation in reflectance.

The best means to differentiate species may not be through pure spectral signature; it may be best to identify spectral regions occupied by the spectral radiance of species relative to neighboring species. Regardless of environmental or biotic influences, it might be assumed that all individuals of a species occupying a particular site will exhibit similar reactions to those influences and, hence, similar changes in spectral reflectance characteristics. The use of statistical analysis may define this region relative to other species growing under the same conditions (Curran and Atkinson 1998). Extensive use could be made of a method to simply identify pine and nonpine located within a pine plantation, but a means to identify the particular species growing in competition with the loblolly pine would be more valuable. Because species separation is desirable for competitive assessment, a need has been identified to assess means to spectrally differentiate loblolly pine and competing hardwood trees in pine plantations.

Spectral separation of pine from competition—The basis of this study relies heavily on the fact that the number of hardwood species in direct competition with loblolly pine in plantation environments is finite. The most important competing species can be grouped to include gums, oaks, hickories, and elms. Theoretically, since species found within an individual pine plantation are subjected to the same influences, it may be possible to assume these species occupy a spectral position relative to each other, which changes in only minor ways with changes in soil moisture, fertility, and other abiotic factors. Based on this assumption, first advanced by Cochrane (2000), it is believed that most of the important competitive woody species will occupy a fairly constant spectral region relative to the region occupied by loblolly pine. Although the spectral relationship between species may change from season to season, it should prove fairly constant during the same season from year to year. This study was undertaken to determine a methodology to separate species based on spectral response.

MATERIAL AND METHODS

Loblolly pine plantations in Attala County, MS, were selected for this study. The site was chosen based on pine plantation ages and site characteristics. The area consists of 1,100 acres of pine plantations, natural pine-hardwood stands, and agricultural fields. Within this study area, three plantations were chosen, and study sites of 1 acre each were selected within each plantation. These sites had been used for cotton production for many years and were planted with loblolly pine the year following the last cotton crop. Site and stand conditions ranged from a low alluvial site with a plantation age of 15 years to an upland site with a plantation age of 18 years. The sites occur in the sand-clay hills physiographic region of Mississippi. The soil was originally overlain by a thin layer of loessial brown loam which has, in most instances, been lost to erosion.

Data Collection

Site locations were accurately defined using a Global Positioning System (GPS). During this phase, site boundaries were established for eventual airborne data collection. Handheld spectroradiometer (HHSR) measurements were taken within each plantation on representatives of major woody species selected for this study. Species were selected based on their position within the canopy of the plantations. Species common to each site and with crowns positioned in the upper canopy with the loblolly pine crop were chosen for this study; they included sweetgum (*Liquidambar styraciflua* L.), winged elm (*Ulmus alata* Michx.), water oak (*Quercus nigra* L.), and white oak (*Quercus alba* L.) and the crop species, loblolly pine.

GPS data collection—A Landmark GPS (Landmark Systems Inc., Tallahassee, FL, U.S.A.) connected to a Juniper Pro4000 (Juniper Systems Inc., Logan, UT, U.S.A.) field computer was used for this study. The system incorporated a Trimble AG132 (Trimble Navigation Ltd., Sunnyvale, CA, U.S.A.) receiver and large dome antenna using an Omni Star Geostationary Satellite (Omnistar Inc., Houston, TX, U.S.A.) for differential correction. Global positioning was used to determine area boundaries of the study sites by latitude and longitude.

HHSR data collection—On-site spectral data were collected using a Field Spec Pro FR portable spectroradiometer (Analytical Spectral Devices, Inc., Boulder, CO, U.S.A.). The HHSR measures spectral responses of reflecting objects in the electromagnetic spectrum range of 350 to 2,500 nm. The device has a spectral resolution of 3 nm from 350 to 700 nm and 30 nm at 1,400 nm and higher. Although the device is capable of providing reflectance data in each of 2,151 individual spectral bands from visible to far infrared, only four multispectral bands were used in this study (green, red, red-edge, and near infrared) as they coincided with available airborne instrument capability used in a companion study. The bands were centered on 550, 675, 700 and 840 nm, respectively, with a bandwidth of ± 5 nm. Extracted multispectral data included each of these bands. A fiber-optic strand is used to transmit electromagnetic energy from the “pistol grip” head to the recording unit; in this study, the bare fiber was used in order to get a wide field of view of foliage. The field of view was approximately 230 at the fiber-optic tip. The tip was held 1.5 feet from the sample to collect spectral radiance information from the entire branch rather than individual leaves. The samples were placed on a 3 by 4 foot black foam-core board for data collection to reduce spectral

noise. The device was calibrated using a white reference tile every 2 to 5 minutes. The calibration was performed to assure changing atmospheric conditions, and battery power did not bias the reflectance values.

HHSR data were collected to document two transition seasons (fall and spring) and midgrowing season (summer) conditions. Data collection was attempted on numerous occasions, but most failed due to inclement weather. Successful data collection was made in November 2001, April 2002, and August 2002 to represent fall, spring, and summer samples, respectively. HHSR measurements were taken between 10:00 a.m. and 2:00 p.m. on cloudless days to insure consistent sun angle and radiance magnitude. The spectral-reflectance data were collected for both loblolly pine and four woody competitors located within the pine plantation study site. On each day that data were collected, representative samples of each species were collected from each study area and immediately measured with the HHSR against a flat black panel. A full branch from the species being collected was cut and oriented upright against the panel in a manner similar to that which would be measured by an airborne sensor. Samples were measured within 3 to 5 minutes of harvest to avoid changes in chemistry and physiology of the plant material. Samples were measured in full sunlight at any convenient open central location adjacent to or within the study area. To reduce noise, all profile measurements were calculated as averages of 20 sampling points. Each sample was taken from a different individual within the study area. Care was taken to collect samples growing in full sun to mimic those clearly visible on aerially collected images. The multispectral data were converted to text format by software provided by the manufacturer of the HHSR. The converted data included the wavelengths, spectral response values, and sample numbers. The converted data were loaded into Microsoft Excel spreadsheet software (Microsoft Corporation, Redmond, WA, U.S.A.). In this format, each sample was labeled for name of the appropriate species recorded for that repetition. The data were arranged by band and grouped by species.

DATA ANALYSIS

Indices, including the normalized vegetation index (NDVI), the normalized vegetation index with green band (NDVIg), red vegetation index (RVI), and the density vegetation index (DVI) were added to the data set and treated as spectral bands (table 1). The indices provided additional "bands" of data previously proven useful in separating vegetation characteristics. These additional bands were added to increase the power of statistical analyses and the chances of accurate classification. The results were eight "bands" for analysis: green, red, RE, NIR, NDVI, NDVIg, DVI, and RVI. All statistical analysis was accomplished using Minitab 13.32 statistical analysis software (Minitab Inc., State College, PA 16801, U.S.A.). The eight bands were then subjected to correlation tests. Statistical analysis was completed by discriminant analysis using each of the band combinations derived from the above steps. The purpose of this analysis was to find a minimal set of bands that, when used in combination, held the best promise for discriminating between species.

Table 1—Vegetation indices used as additional bands in multispectral data analysis

Index name	Index formula
NDVI	NIR-Red/NIR+Red
NDVIg	NIR-Green/NIR+Green
RVI	NIR/Red
DVI	NIR-Red

NDVI = normalized vegetation index; NDVIg = normalized vegetation index with green band; RVI = red vegetation index; DVI = density vegetation index.

Correlation analysis—Huberty and Wisenbaker (1992) reported that using correlated bands in combination will result in discriminant analysis functions with false positive classification accuracy results. To eliminate variables (bands), which would tend to skew discriminant power, a correlation analysis was performed for all bands and indices in combination. Bands found to be correlated with other bands were removed from the final analysis.

Discriminant analysis—Discriminant analysis was conducted to test the performance of those bands in separating spectra into species classes. The species groups and band data were used as the response and predictor variables in the discriminant analysis, respectively. After analysis, species were cross-validated in a user accuracy test to determine the power of the resultant discriminant functions. Discriminant analysis is an unambiguous mathematical method to determine the identity of an unknown sample. A good discriminant function can recognize the spectral reflectance of a species by use of a training set of known spectral signatures of that species. Samples in the training set are assumed to represent the variance of the reflectance for a particular species. Discriminant analysis allows the construction of models for each known species that can be compared to samples of unknown species in an attempt to classify it. The reflectance of the unknown sample is compared to multiple models of different species. The models can then predict the likelihood that the sample matches the training spectral responses by returning a "yes" or "no" answer (Thermo Galactic 2002).

In Predictive Discriminant Analysis (PDA) in this study, the multiple response variables play the role of predictor variables, much like a regression equation. Analysis of the variables will predict the proper classification of unknown species reflectance values into the known species group. Accuracy of these predictions is a direct result of the accuracy of the data set used to "train" the discriminant function. These training sets are made more accurate by tests for linear relationships to eliminate problems with error capitalization due to correlation between variables (Huberty and Wisenbaker 1992). Although step-wise discriminant analysis is successfully used for a variety of data analyses, it was not used with these data because of the inherent problems this method presents. Step-wise analysis tends to calculate incorrect degrees of freedom, capitalizes on relatively small sampling error (Whitaker 1997), and does not necessarily identify the best predictors

of a given data-set size (Thompson 1995). Since the probability of any sample falling within any given species classification is not known, the statistical method assumed prior probabilities were even; that is, the probability of a sample being classified into any species class is assumed to be equal throughout the data set.

When discriminant analysis was performed using the data collected for this comparison, squared distances between spectral signatures of the species groups were calculated. The clearest advantage of using squared distances is that the distances are calculated in units of standard deviation from the group mean. This allows an assignment of a statistical probability to the measured distance from one species mean to the other. Squared distances are reported here and used in this study to determine if spectral response of each species occupies a specific spectral region in relation to the spectral response of the other species. In theory, sample spectra with a squared distance of 3 nm or greater from a known species spectra have a probability of 0.01 or less of belonging to that species. Samples with a distance of less than 3 nm are then classified as members of the species. However, in practice, using aerial or satellite images, researchers have found that a distance of 10-15 nm works best as a maximum variance for classification of data (Thermo Galactic 2002).

The drawbacks to using squared distances include the fact that discriminant analysis relies on selecting a subset of bands to represent the entire spectrum for a species. More bands can not be added to increase accuracy, however, because the method tends to "over fit" very quickly. Using a combination of more than 10 to 15 bands can lead to Type I errors: failing to classify species into a group in which they belong (Thermo Galactic 2002). Although the squared distances reported for this study are two dimensional and can relate only to the distances between two species spectral regions, it is still useful in comparing those two species. The comparison of the spectral distance between loblolly pine and its competitors will prove useful in determining if the spectral regions are far enough apart to allow separation of the two species. With a maximum of four bands of spectral data used in these analyses, using a two-dimensional approach should not result in Type I errors.

RESULTS AND DISCUSSION

The multispectral data were analyzed by season of acquisition with all measurements for each collection date grouped by species. For each season, correlation tests, PCA, and discriminant analysis were performed to identify the bands suitable for correctly classifying the species of interest.

Table 2—Pearson correlation coefficients of spectral values for loblolly pine and four woody competing species from HHSR samples taken in pine plantations in Attala County, MS

	Green	Red	Red edge	NIR	NDVI	NDVIg	RVI
Spring (April 2002)							
Red	0.43						
Red edge	0.90	0.62					
NIR	0.63	-0.15	0.53				
NDVI	0.32	-0.64	0.16	0.77			
NDVIg	0.14	-0.50	0.13	0.80	0.87		
RVI	0.28	-0.60	0.11	0.87	0.89	0.87	
DVI	0.55	-0.28	0.43	0.99	0.84	0.85	0.93
Summer (August 2002)							
Red	0.76						
Red edge	0.92	0.71					
NIR	0.34	0.20	0.33				
NDVI	-0.35	-0.61	-0.27	0.62			
NDVIg	-0.34	-0.28	-0.24	0.75	0.86		
RVI	-0.45	-0.70	-0.40	0.46	0.89	0.73	
DVI	0.27	0.11	0.27	1.00	0.69	0.79	0.54
Fall (November 2001)							
Red	0.23						
Red edge	0.49	0.82					
NIR	0.33	-0.09	0.30				
NDVI	-0.14	-0.91	-0.62	0.48			
NDVIg	-0.75	0.26	-0.26	0.35	0.45		
RVI	-0.33	-0.79	-0.71	0.39	0.87	0.58	
DVI	0.22	-0.43	-0.01	0.94	0.74	0.41	0.63

HHSR = handheld spectroradiometer; NDVI = normalized vegetation index; NDVIg = normalized vegetation index with green band; RVI = red vegetation index; DVI = density vegetation index.

Correlations—Each band and all indices were tested for correlation. In both the fall and spring data, the RVI, NDVI, and DVI were correlated with most other bands (table 2). The correlation of the indices with one or more of their component bands was expected. Unexpectedly, green was found to be highly correlated with red (Pearson correlation coefficient of 0.76) in the August data and with NIR in the April data. This was an interesting phenomenon in that combinations including green, red, and NIR see widespread use for classification purposes. Although the NDVIg index is a function of both the green and NIR bands, it was found to be correlated with only one or the other of its components in any single data set. The significance of this relationship is not known.

Bands were chosen for inclusion in further analysis by direct observation of the correlation matrices and manually selecting combinations of bands not correlated with any other bands in the proposed combination. Bands were assumed to be correlated if the Pearson correlation coefficients were between 0.60 and 1.00 (positive correlation) and -1.00 and -0.60 (negative correlation). Possible variable combinations remaining after correlation tests are shown in table 3. It is interesting to note that only the August and November data have a combination in common (combination two - green, NIR, and RVI).

Discriminant analysis—Discriminant analysis revealed that there was no real difference between classification accuracy of the April and November data sets. The discriminant function classified species with 82-and 83-percent accuracy using the November and April HHSR data, respectively (table 4). The August data performed much less effectively. The best classification accuracy was 51 percent and used the combination of red, NIR, and NDVI. The highest classification accuracy obtained with the spring data was the combination of the green, red, and DVI bands. For the November data, the combination of green, NIR, and RVI was most effective.

Species classification accuracy—A band combination common to both the November and August data sets (Combination 2, table 3) was the most effective band combination for predicting species classification in the November data and the least effective when used for the August data. The green, NIR, and RVI combination in the August data correctly classified species to class with only 41 percent accuracy but with 82 percent accuracy using the November data (table 4). This indicates that the widespread use of standard band combinations (i.e., green, red, NIR) or indices may not return the highest and most accurate classification for any two data sets. Because loblolly pine is the crop species and most important in classification accuracy, observations on classification of this species are of particular importance. With the April data set, loblolly pine was 100 percent correctly classified (table 5). However, in the November data set, classification accuracy was only 80 percent, with loblolly erroneously classified as winged elm. Although overall classification accuracy (table 4) was statistically the same for both the April and November samples, the fact that the crop species was always correctly classified in the April data makes this season more attractive for separating this species from its main competitors. Winged elm was incorrectly classified 40

Table 3—Usable band and indices combinations derived from statistical tests of seasonal HHSR data

	Combination 1	Combination 2	Combination 3
April	Green, Red, NDVIg	Green, Red, RVI	Green, Red, DVI
August	Green, Red, NDVIg	Green, NIR, RVI	Red, NIR, NDVI
November	Green, Red, NIR	Green, NIR, RVI	NIR, NDVIg, RVI

HHSR = handheld spectroradiometer; NDVI = normalized vegetation index; NDVIg = normalized vegetation index with green band; RVI = red vegetation index; DVI = density vegetation index.

Table 4—Overall classification accuracy of band combinations using discriminant analysis of multispectral bands and indices

Data set	Most effective band combination	Classification accuracy
		percent
April	green, red, DVI	83
August	green, NIR, NDVI	54
November	green, NIR, RVI	82

DVI = density vegetation index; NDVI = normalized vegetation index; RVI = red vegetation index.

Table 5—Percentage of loblolly pine and four competing woody species' samples correctly classified to species group using discriminant analysis functions

	Species groups				
Data set	LOB	SWG	WAO	WHO	WIE
	- - - - - - - - - - *percent* - - - - - - - - - -				
April	100	83	100	75	60
August	50	56	19	75	56
November	80	100	75	67	100

LOB = loblolly pine; SWG = sweet gum; WAO = water oak; WHO = white oak; WIE = winged elm.

percent of the time in the April dataset but was correctly classified 100 percent of the time in the November data set. Forty percent of winged elm was classified as white oak using the April data. Thirty-three percent of white oak was classified as water oak using the November data, and 25 percent was classified this way in the April data. This may indicate that the oaks are somewhat similar in reflectance during most of the year. However, control prescriptions may not need to be altered by any misclassification of these species since current control methods are similar for most oak species.

Squared distances and misclassification—One of the hypotheses of this study is that species reflectance values may occupy spectral regions that stay constant in relation to their distances from the spectral regions of other species. If this theory were correct, then species separation using spectral reflectance would prove successful regardless of biotic and abiotic influences on the species because all species on a particular site would be subject to the same influences. An observation of the squared distances between loblolly pine and four competitive hardwood species examined in this study proves this theory is not upheld from season to season. The squared distances between the spectral range of loblolly pine and its competitors vary by season (table 6); the average squared distances become much less during the August period. Although the table indicates the average squared distances for all samples, reflectance values of individual trees may be much closer, thus indicating the standard deviations of spectral values change dramatically due to seasonal influences. In the November data set, loblolly pine was misclassified as winged elm. The average squared distance between the misclassified loblolly pine and winged elm samples was 1.598 nm. The probability of loblolly being classified as winged elm was 52.8 percent due to close spectral proximity of the two species. In this particular study, overall seasons and all data, misclassifications occurred when the squared distances were less than or equal to 8.6991 nm. The mean squared distances between species misclassified was 2.507, and the median squared distance was 2.151 with a standard deviation of 1.75505. Standard error of squared distances between misclassified species was 0.2676. It is assumed that the threshold misclassification level of mean squared distances given are unique to this study and can not be assumed for all spectral response studies.

Table 6—Average squared distances between loblolly pine spectra and the spectral regions of selected hardwood species based on band combinations[a] with highest overall classification accuracy

Species	April	August	November
Water oak	6.7792	5.3399	5.9066
Sweetgum	13.0503	9.8167	16.0741
White oak	15.3399	4.7059	15.5052
Winged elm	11.0394	3.8657	9.4649

[a]April = green and red bands and density vegetation index, August = red and NIR bands and normalized vegetation index, and November = green and NIR bands and red vegetation index.

Many classification tasks undertaken in standard "off the shelf" remote sensing software require the user to input a maximum squared distance between spectral responses required in order to place a spectral response in a particular class. As discussed earlier, current theory indicates that samples with a squared distance of 3 nm or greater have a probability of 0.01 or less of belonging to that species, and that in actual practice users will use a distance of 10 to 15 nm (Thermo Galactic 2002). If this study is an indicator of actual results, a user-defined squared distance of 9 to 10 nm will return more accurate results and may reduce "unclassified" spectral responses. However, it cannot be stated for certain that the results of this study are globally useful.

Seasonal influences on classification accuracy—When comparing the seasons in which data were collected, the spring transitional season had the best overall accuracy for species separation and was best for separation of loblolly pine from the competitive species. During this season, the competitive and largely deciduous species are in the "green up" process. That is, these species have new growth and young foliage. Loblolly pine still retains its old needle foliage from the preceding year and does not replace 2-year-old needles with new foliage until later in the season. Concentrations of chlorophyll will differ greatly during this period. Chlorophyll concentrations have more influence on spectral responses in the 400-to 700-nm range of electromagnetic wavelengths (Tucker and Garrett 1977). Although the competitive species are in varied stages of transition during this time period, most of the foliage on the species is new growth (water oak individuals were observed to have some retained foliage from the preceding year). This similarity in foliage growth stage may explain the variability in classification accuracy between the competitive species (60 to 100 percent). Gausman (1985) and Atkinson and others (1997) found that foliage age causes variation in reflectance response.

The summer season is least useful; the spectral response of the older foliage of all species becomes less well-defined. The classification accuracy between deciduous species ranges from 67 to 100 percent using the fall data, but spectral confusion is introduced when comparing these species with loblolly pine. The greater classification accuracy from fall data may be a function of the chemical changes taking place in leaves in the fall in preparation for winter dormancy. Chlorophyll begins breaking down, which "unmasks" other pigments. However, confusion in the identification of pine with the competitor winged elm is an undesirable effect.

SUMMARY AND CONCLUSIONS

Based on this study, the spring transition period appears most valuable in determining the level of competition within loblolly pine plantations using remote sensing reflectance data. The overall accuracy of 83 percent is similar to the 82-percent accuracy obtained using fall transition data, but loblolly pine can be completely separated from the

competitive species in April. Using remote sensing reflectance data, a forest manager may make decisions on competition control based solely upon the proportion of nonpine species observed in the upper canopy. If this controlled study can be carried over into an operational environment, it may prove particularly beneficial. However, making these discoveries operationally useful will require further study. The methods and findings of this study will need to be applied to data collected by remote sensors in an operational setting to determine if the results are similar.

Remote sensing methods used in this study are not without problems. Weather plays a major role in the collection of remotely acquired data. The spring transition period normally has many cloudy and stormy days; however, sunny days of pristine atmospheric conditions also occur. Flexibility in scheduling is the key to data acquisition. Even with extensive funding from NASA's Stennis Space Center, problems occurred with data storage, data loss, and scheduling. This reinforces observations that these problems will likely occur with any system of data collection until routines and methods are established that safeguard against mishaps.

Remote sensing holds great promise in reducing *in situ* visits for forest competition assessment. It is anticipated that future access to hyperspectral remote sensors (more bands for greater discrimination) with finer spatial resolution than what is currently commercially available will open the way to widespread use of remote sensing to identify competitive species in tree plantations.

ACKNOWLEDGMENTS

The authors thank the National Aeronautics and Space Administration (NASA) and the John C. Stennis Space Center for funding and support of this research. Thanks go to Louis Wasson and staff of the Remote Sensing Technology Center at Mississippi State University for their help with field and lab work. Finally, thanks go to Mr. Harvey Black for allowing unfettered access to his property and loblolly pine plantations during the course of this research.

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RELATIONSHIP BETWEEN CANOPY DYNAMICS AND STEM VOLUME PRODUCTION OF FOUR SPECIES RECEIVING IRRIGATION AND FERTILIZATION

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Abstract—We measured the effects of irrigation and varying levels of fertilization on intercepted photosynthetically active radiation (IPAR), projected leaf area index (LAI), and foliar nitrogen concentration ([N]) in order to determine the relationship between resource availability, canopy size, and stem-volume growth. Stands of sycamore (*Platanus occidentalis* L.), sweetgum (*Liquidambar styraciflua* L.), loblolly pine (*Pinus taeda* L.), and slash pine (*Pinus elliottii* Engelm.) planted in 1997 near Mount Pleasant, GA, received five treatments: control, irrigation only, and irrigation with 57, 85, and 114 kg N ha^{-1} $year^{-1}$. Beginning in March 2001, sampling for foliar [N], IPAR, and leaf litter were conducted approximately every 6 weeks. Irrigation and fertilization increased stem-volume growth during the 2001 growing season. Annual IPAR and LAI were well correlated with stem-volume growth ($r^2 = 0.80$, $r^2 = 0.75$, respectively—averages of four species). Foliar [N] and stem-volume growth were significantly correlated for sweetgum ($r^2 = 0.76$) and sycamore ($r^2 = 0.80$). These results indicate that IPAR is the best predictor and may be the primary driver of stem-volume growth.

INTRODUCTION

The positive impact of fertilization on site productivity depends on nutrient application rates and frequency, genotypic variation (within and between species), inherent site factors (e.g., climate, soil factors, relief, etc.), and complimentary cultural treatments (e.g., site preparation, weed control, thinning, etc.). Whereas growth enhancements are well documented (Fife and Nambiar 1997, Lockaby and others 1997, Maier 2001), the reasons for increased growth are less evident. Several factors related to canopy dynamics have been identified as potential drivers of growth accelerations; some are fertilization, including increased foliage development for light interception and photosynthetic surface area (Albaugh and others 1998, Beets and Whitehead 1996, Samuelson 1998), increased photosynthetic capacity (Murthy and others 1996, Samuelson 2000), and increased partitioning of fixed carbon to aboveground biomass (Albaugh and others 1998, Gower and others 1992, Keyes and Grier 1981). A better understanding of the mechanisms driving growth hopefully will permit better management regimes and increase the precision of growth predictions using process-based models, such as 3-PG, MAESTRO, and BIOMASS.

Nitrogen fertilization usually increases foliage development (Kuers and Steinbeck 1998, Sampson and Allen 1998). This has a positive impact on growth by increasing surface area for carbon fixation and by increasing the amount of radiation intercepted by the stand. Although photosynthetic surface area and radiation interception are both mediated by foliage development, their relationship differs between stands or with stand development due to differences in foliage display. Nitrogen fertilization also often increases foliar nitrogen concentration (Beets and Whitehead 1996; Jose and others, in press; Maier 2001; Nelson and others 1995). This increase may correspond to subsequent increases in photosynthetic capacity (McMurtrie and others 1990, Murthy and others 1996, Samuelson 2000). However, in some cases such as mature pine stands, higher foliar nitrogen concentrations do not stimulate photosynthesis (Maier and others 2002; Munger and others, in press).

Water availability, like fertilization, can have a large positive effect on stand growth, especially when water is limiting (Jose and others, in press; Li and Wang, in press; McMurtrie and others 1990; Samuelson 1998; Samuelson and others 2001). In other instances, irrigation had little impact on growth of forest stands (Albaugh and others 1998, Maier 2001). Water stress may (Li and Wang, in press;Osorio and others 1998; Wendler and Millard 1996) or may not (Albaugh and others 1998, Green and others 1994) decrease leaf-area development. Likewise, irrigation may dilute foliar nitrogen concentration (Jose and others, in press; Samuelson and others 2001) or may have no effect (Murthy and others 1996, Samuelson 1998).

The objectives of this study were to (1) determine how various levels of resource availability, as altered by irrigation and fertilization, impact leaf area index (LAI), intercepted photosynthetically active radiation (IPAR), and foliar nitrogen concentration ([N]) of four fast-growing tree species (*Pinus taeda* L., *Pinus elliottii* Engelm., *Liquidambar styraciflua* L., and *Platanus occidentalis* L.), and (2) relate the responses of LAI, IPAR and [N] to stem-volume growth.

METHODS

Study Description

The study site was located in the Lower Coastal Plain, near Mount Pleasant, GA, (31°23'N, 81°43'W). Soils were deep, acidic sands that previously supported a pine plantation. In 1997, loblolly pine, slash pine, sweetgum, and sycamore were planted in 0.10-ha plots at a density of 1,790 trees

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

ha^{-1} to test the effects of irrigation combined with increasing fertilization rates. The study was a randomized complete block design, with five treatments replicated over three blocks. The treatments were as follows (with treatment codes): control (C), 3.05 cm water $week^{-1}$ (I), 3.05 cm water $week^{-1}$ + 57 kg N ha^{-1} $year^{-1}$ (I + N57), 3.05 cm water $week^{-1}$ + 85 kg N ha^{-1} $year^{-1}$ (I + N85), and 3.05 cm water $week^{-1}$ + 114 kg N ha^{-1} $year^{-1}$ (I + N114). Treatments were initiated during the first growing season. During the 2001 growing season, fertilizer was applied as 12-4-8 N-P-K with micronutrients.

Volume Estimation

Dormant season diameter at breast height (d.b.h.) and total height were measured annually on every tree. Stem-volume equations were calculated using taper measurements of 180 harvested trees (45 per species) at the end of the 2002 growing season. Three trees per plot were selected for harvest based on prior determinations of d.b.h. distribution (mean d.b.h., mean d.b.h. ± standard deviation). Taper was calculated by measuring stem diameter at ground line, 1 m, d.b.h., 2 m, and every subsequent 2-m interval. A single taper equation was used for each species, as linear regression analysis showed no difference between treatments within a given species. Taper equations were used to calculate volume at the end of the 2000 and 2001 growing seasons using the annual measurements of height and diameter. Growth during the 2001 growing season was calculated as the difference in standing volume at the end of the 2001 and 2000 growing season. No mortality occurred during the 2001 growing season.

Intercepted Radiation

Measurements of IPAR were made under cloud-free conditions every 30 to 60 days during the 2001 growing season (six total measurements) with the Sunscan Canopy Analysis System (Delta-T Inc., UK). Percent IPAR per plot was calculated based on incident radiation and the average of 50 subsamples beneath the canopy (IPAR = 1 - canopy transmittance/incident radiation). As zenith angle has a large effect on radiation interception, IPAR was corrected to a standard angle of 30° with empirically derived equations. To derive these correction equations, hourly measurements were made in plots of each species and treatment combination during midsummer. From these measurements, regression equations were derived [IPAR = a + b (zenith angle)^2] for each species treatment combination. Annual energy capture was calculated by interpolating percent IPAR between sampling dates, multiplying by average incoming radiation for each day, and then summing the daily totals. Solar energy data from the National Solar Radiation Database (Renewable Resource Data Center, U.S. Department of Energy) were used for daily incident radiation values. The most recent data available (1981-90) from Savannah, GA, (closest weather station) were averaged.

Leaf Area Index

Projected LAI was determined from litter biomass collected from five randomly placed litter traps per plot (trap area = 0.47 m^2). Leaf litter was collected monthly after the initiation of leaf senescence (around October) and continued through mid-January. Pine litter also was collected several times during the growing season. Leaf litter was dried at 70 °C and weighed. Monthly biomass collection weights were summed and scaled to the hectare basis. Litter biomass was converted to LAI using estimates of specific leaf area (average of four growing-season measurements) and empirically derived factors to adjust for weight loss between fresh leaves and litter. For pines, all-sided LAI was converted to projected LAI by dividing by 3.14 (Grace 1987).

Foliar Nitrogen Concentration

Samples for foliar [N] were collected four times during the growing season using a shotgun. On each sampling date, three pine or four hardwood foliar samples were collected from the upper third of the canopy of each plot. Pine foliage was separated into the two age cohorts (when present), and several representative fascicles were collected from each flush. Samples were kept on ice until placed in an oven to dry at 70 °C. After drying, samples were ground to a fine powder with an 8000-D mixer mill (Spex Certiprep, Inc., Metuchen, NJ) and analyzed for [N] with a NA 1500 nitrogen/carbon analyzer (CE Elantech Inc., Lakewood, NJ, USA).

Statistical Analysis

Separate analyses were conducted to determine the effect of irrigation (C vs. I) and the effect of fertilization (I, I + N57, I + N85, I + N114). For standing volume, volume growth, annual energy capture, LAI, and average foliar [N], the effect of fertilization was determined with analysis of variance (ANOVA) whereas the effect of irrigation was analyzed with a Student's t-test. Linear regression analysis was used to correlate IPAR, LAI, and foliar [N] with stem-volume growth and included irrigated and non-irrigated plot data.

RESULTS

Volume

Fertilization in conjunction with irrigation increased standing stem volume when compared to irrigation alone. Although there were no significant differences between the three levels of fertilization, the I + N85 treatment consistently resulted in the highest standing volume, showing 57-percent, 69-percent, 514-percent, and 209-percent gains over the I treatment for slash pine, loblolly pine, sweetgum, and sycamore, respectively (fig. 1). Compared to the control, irrigation significantly increased standing volume only for hardwood species (sweetgum, 103 percent; sycamore, 340 percent) (fig. 1).

For the 2001 growing season, fertilization significantly increased volume growth for sweetgum and sycamore, with increases of 160 percent and 667 percent, respectively, for the I + N85 treatment compared to the I treatment (fig. 1). Although not statistically significant due to variation between blocks, loblolly pine and slash pine stem-volume growth increased by 52 percent and 65 percent, respectively, due to fertilization. Both hardwood species showed large increases in stem growth during the 2001 growing season due to irrigation (sweetgum, 343 percent; sycamore, 1980 percent).

Intercepted Radiation

Fertilization increased annual IPAR for loblolly pine, slash pine, sweetgum, and sycamore, with increases of 31, 40, 253, and 41 percent, respectively (fig. 2). In all cases, the

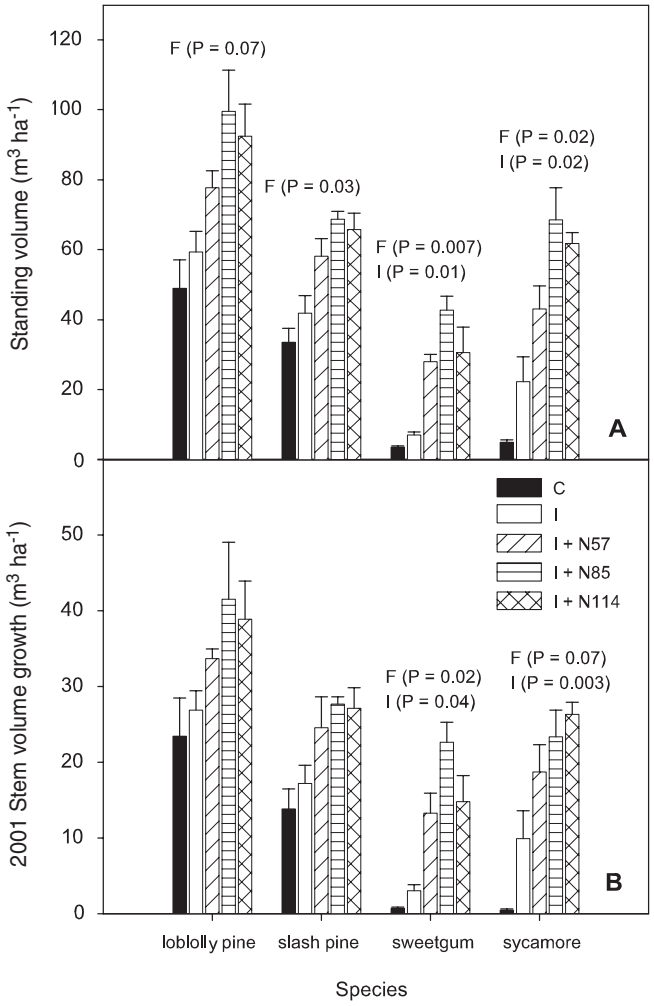

Figure 1—Standing volume at the end of the 2001 (fifth) growing season (A) and 2001 stem-volume growth (B). Treatment codes represent: C = control; I = 3.05 cm water week^{-1}; I + N57 = 3.05 cm water week^{-1} + 57 kg N ha^{-1} year^{-1}; I + N85 = 3.05 cm water week^{-1} + 85 kg N ha^{-1} year^{-1}; I + N114 = 3.05 cm water week^{-1} + 114 kg N ha^{-1} year^{-1}. F indicates a significant effect of fertilization, I indicates a significant effect of irrigation with P-values in parentheses (bars represent 1 standard error).

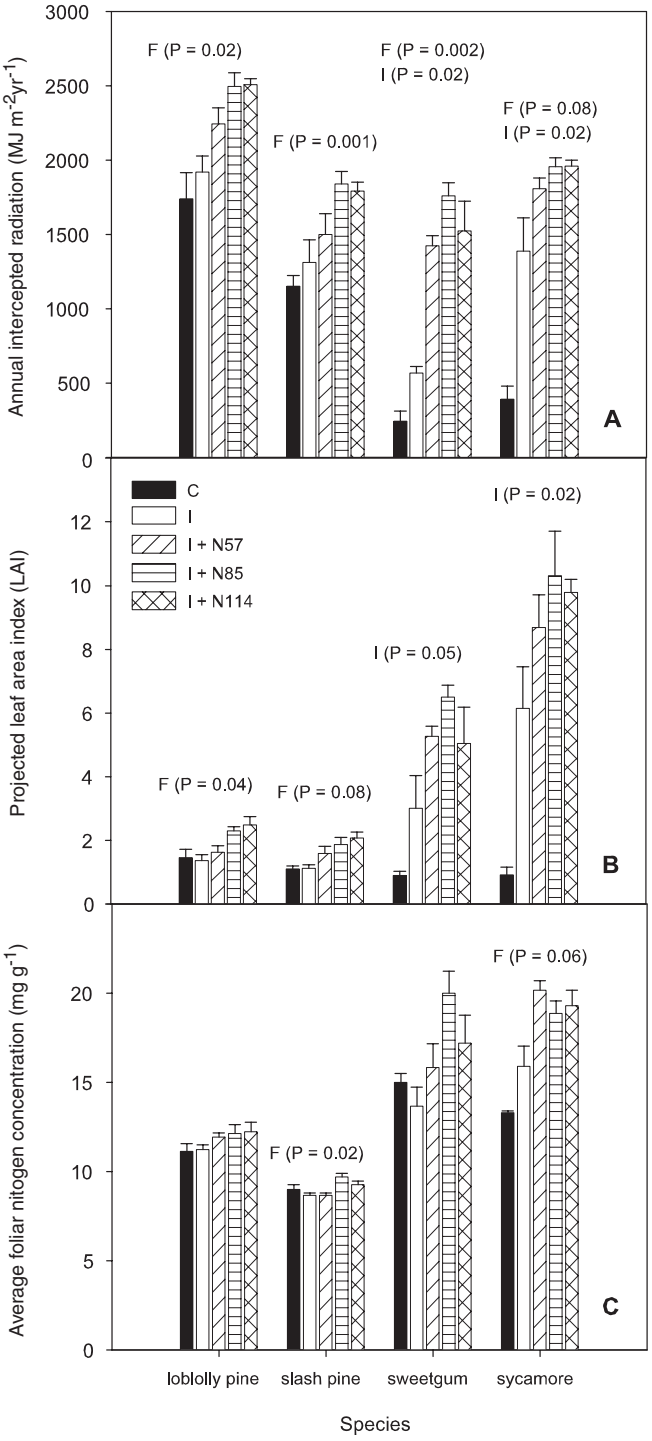

Figure 2—Annual intercepted radiation (A), projected LAI (B), and average foliar nitrogen concentration (C) for the 2001 (fifth) growing season. Treatment codes represent: C = control; I = 3.05 cm water week^{-1}; I + N57 = 3.05 cm water week^{-1} + 57 kg N ha^{-1} year^{-1}; I + N85 = 3.05 cm water week^{-1} + 85 kg N ha^{-1} year^{-1}; I + N114 = 3.05 cm water week^{-1} + 114 kg N ha^{-1} year^{-1}. F indicates a significant effect of fertilization, I indicates a significant effect of irrigation with P-values in parentheses (bars represent 1 standard error).

mid- and high-level fertilization treatments showed the largest enhancement, although differences were not significant among the three fertilization treatments. Irrigation caused large increases in the radiation interception of hardwood species, with sweetgum and sycamore showing 133 percent and 253 percent increases, respectively. Annual IPAR was highly correlated with stem-volume growth during the 2001 growing season for all species (fig. 3).

Leaf Area Index

Only the 2000 cohort of foliage (cohort on the tree for the entire 2001 growing season) was available for estimation of pine LAI; however, it was shown that fertilization increased LAI for both species of pine. Although differences among fertilization treatments were small, the I + N114 treatment resulted in the largest gain over the I treatment, with increases of 68 percent and 88 percent for loblolly and slash pine (fig. 2). Although fertilization did not significantly affect LAI for either hardwood species, the I + N85 treatment increased LAI by 116 percent and 66 percent for sweetgum and sycamore, respectively. Irrigation increased LAI for hardwood species (sweetgum, 233 percent; syca-

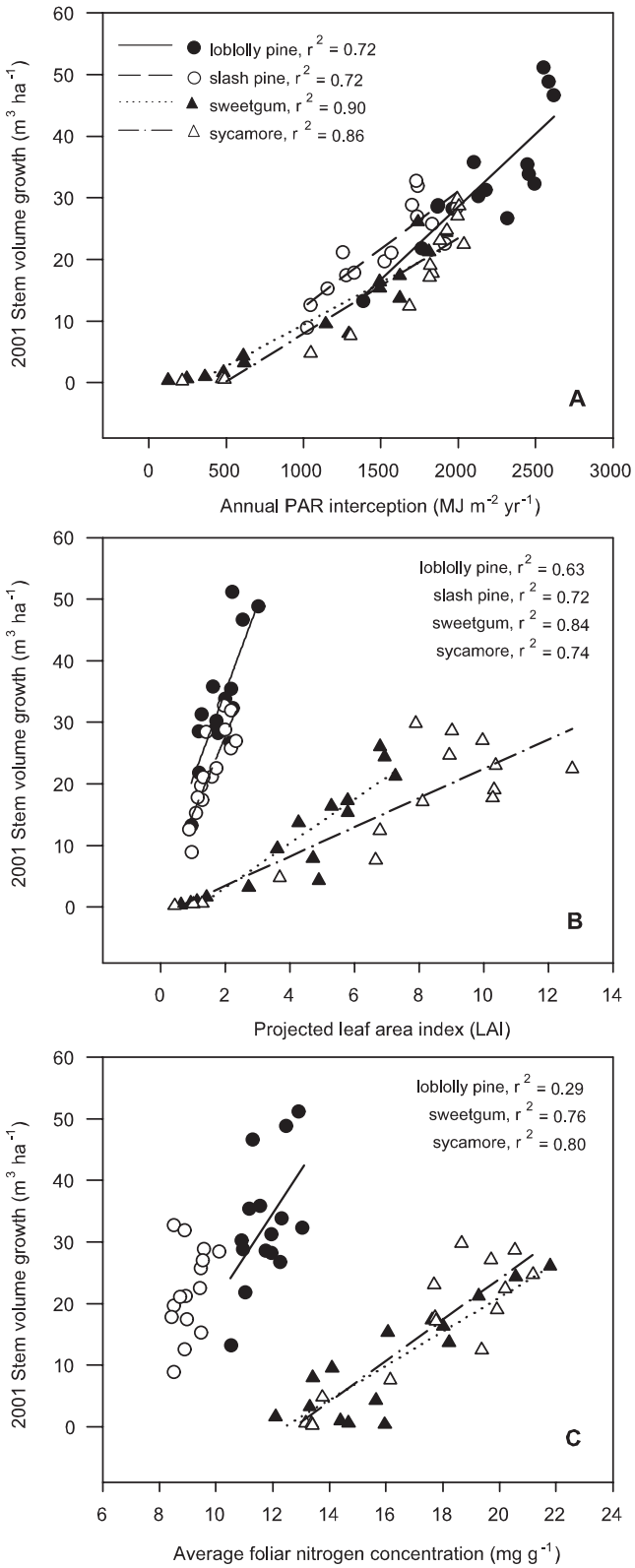

Figure 3—Relationships between 2001 (fifth growing season) stem-volume growth and annual intercepted radiation (A), projected LAI (B), and average foliar nitrogen concentration (C).

more, 589 percent) but did not affect either of the pine species (fig. 2). Good correlations were found between projected LAI and 2001 stem-volume growth for all species (fig. 3). The relationships for hardwood and pine species were distinct from one another, although this distinction would be less if the 2001 foliage cohort were included in estimates of pine LAI.

Foliar Nitrogen Concentration

Fertilization significantly affected average foliar [N] for slash pine and sycamore whereas irrigation had no significant effects (fig. 2). In the hardwood species, values of [N] were higher and more variable than those of the pines and tended to increase more with fertilization. Average [N] was highly correlated with stem volume growth for sweetgum and sycamore, both of which exhibited similar regression lines (fig. 3). There was a weak correlation between stem-volume growth and [N] for loblolly pine and no statistical relationship for slash pine.

DISCUSSION

Fertilization increased standing volume and volume production during the 2001 growing season. Although there were no significant differences between fertilization treatments, the highest growth occurred at the intermediate fertilization level. This probably indicates that annual application of 85 kg ha^{-1} of N at this point in stand development was meeting nutrient demand and that adding more may have had a negative impact. As the stands continue to grow and take up more nitrogen, the higher levels of nitrogen fertilization may result in additional growth increases. A similar study on *Pinus radiata* (D. Don) (Fife and Nambiar 1997) showed no differences in growth at the two highest levels of fertilization. Hardwood species responded more to application of resources than did pine species. Specifically, sycamore showed the largest gains from irrigation whereas sweetgum benefited the most from fertilization. A short rotation trial in the Coastal Plain of Alabama found similar results—that fertilization increased height and d.b.h. of both sycamore and sweetgum, and irrigation increased these parameters for sycamore only (Lockaby and others 1997).

Increases in canopy size due to resource addition were similar to those for stem growth. As a result, IPAR and LAI were well correlated to stem-volume growth. Many other studies found linear relationships between growth and IPAR (Cannell and others 1987, Dalla-Tea and Jokela 1991, Landsberg and Wright 1989, Linder 1985, Monteith 1977, Will and others 2000) and LAI (Albaugh and others 1998, Samuelson and others 2001). A study on slash pine in Florida, however, found no relationship between IPAR and NPP (Gholz and others 1991).

In this study, it was not possible to determine causal relationships. However, IPAR explained a larger amount of the variation in stem-volume growth than did LAI, possibly indicating that radiation interception may be more important for determining stem growth than photosynthetic surface area. Also, similar relationships between hardwoods and pines for IPAR may indicate a functional relationship between IPAR and growth regardless of genotype or canopy architecture. In contrast, the relationship between LAI and stem growth differed for hardwoods and pines (even if the 2001 cohort was added to estimates of LAI).

Foliar [N] was higher, the range among treatments greater, and the correlation between stem growth and [N] better in

the hardwood stands than in the pine stands. Fertilization usually increases in foliar [N] of pine (Beets and Whitehead 1996, Fife and Nambiar 1997; Jose and others, in press; Maier 2001; Murthy and others 1996). However, the response may depend on inherent site fertility. For instance, a loblolly pine fertilization study in North and South Carolina found elevated foliar [N] with fertilization for only two of three locations (Vose and Allen 1988). The lack of correlation between foliar [N] and growth for the pine species in our study could be due to the small response or use of nitrogen applied as fertilizer by pines for foliar development and other uses (N dilution).

The results obtained in this study indicate that both IPAR and LAI can be useful predictors of stand growth of different species under a wide range of resource availabilities. In this case, foliar nitrogen concentration had good predictive capabilities for hardwood species but not for either of the pine species. The ease of IPAR measurements compared to those for LAI as well as the better correlations make IPAR measurements the best candidate as a predictor of stand growth.

ACKNOWLEDGMENTS

We thank Robert McGarvey for his aid in the collection of data that otherwise would have proven unattainable, as well as Dr. Robert Teskey and Dr. Mark Coleman for their valuable comments on the manuscript. We also thank Plum Creek Timber Company for funding and assistance and the Traditional Industries Program for Pulp and Paper (TIP^3) for funding.

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GROWTH RESULTS FROM 20-YEAR-OLD LOW DENSITY PINE PLANTATIONS

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Abstract—In 1994, under a cooperative effort between Temple-Inland Forest Products Corporation and Stephen F. Austin State University, 84 permanent research plots were established in two loblolly pine (*Pinus taeda*) plantations in eastern Texas. The study was designed to evaluate the effects of heavy thinning, pruning, fertilization, and competition control on future growth and yield. Three different levels of thinning treatments on randomly selected plots reduced basal areas to 36, 60, and 84 square feet (approximately 100, 200, and 300 stems, respectively) per acre. All residual trees were pruned to a height of 25 feet. Treatments also included two levels of fertilization (fertilized and not fertilized) and two levels of competition control (herbicide and no herbicide). The objective of this paper is to summarize the growth responses on these research plots 8 years after application of cultural treatments.

INTRODUCTION

Intensive management of loblolly pine (*Pinus taeda*) plantations, also known as sudden sawlog management, has gained much attention since the initial reporting by Burton (1982). Over the past two decades, several studies have reported large gains in growth following aggressive fertilization and control of competing vegetation (Borders and Bailey 2002, Miller and others 1991, Pienaar and Shiver 1993). Multiple studies have found increased diameter growth following heavy thinning as well (Holley and others 1999, Wiley and Zeide 1992, Zahner and Whitmore 1960).

In 1994, Temple-Inland Forest Products Corporation (TIFPC), in cooperation with Stephen F. Austin State University, established 84 monumented experimental plots in two typical loblolly pine plantations in eastern Texas. This project, based on studies reported by Burton (1982) and Wiley and Zeide (1992), was designed to evaluate the effects of heavy thinning, pruning, fertilization, and competition control on sawlog production. The overriding goal was to economically produce large clear sawtimber on short rotations. The objective of this paper is to report growth results 8 years after application of cultural treatments.

METHODS

Data for this project come from long-term growth research plots located across two stands in eastern Texas, near the western edge of the southern pine forests. The two study sites differ in relation to soil drainage type. Site 1 is located in the southern corner of Angelina County and is considered a moderately drained site with a Moswell complex (Dolezel 1988). Site 2 is located in southeastern Anderson County and is considered a well-drained site with a Fuquay series (Coffee 1975). Both study areas were on nonold-field sites that were previously forested with loblolly pine and were planted with a local variety seed source. Sites 1 and 2 were planted in 1981 and 1982, with 1,080 and 611 trees per acre surviving in 1988 and 1993, respectively. At the time of plot establishment, the understory at site 1 was almost nonexistent, whereas site 2 contained a heavy mix of woody shrubs and hardwood saplings.

The study was implemented during the summer of 1994, while the stands were in their 14th and 13th growing season, respectively. Plots were positioned within the two stands in a strip-wise pattern as close together as possible while maintaining uniformity and avoidance of windrows, skid roads, drainages, trails, and other anomalies. Each plot consisted of a square one-quarter-acre inner plot surrounded by a 33-foot-wide buffer. Plot buffers received the same treatment as the plot they surrounded but were not used in data collection. Each tree within a plot was measured for diameter outside bark (inches) at 2, 4.5, and 6 feet above ground level, total height in feet, height to first live branch in feet, and crown width in feet. Presence of fusiform rust (*Cronatium quercuum* f. sp. *fusiforme*), crooks, forks or other defects were also tallied.

After plot boundaries were established and tree data were recorded, each plot was revisited for treatment selection and set-up. Three treatments were installed in a completely randomized, without replacement, factorial design with three replications per treatment. Treatments included three levels of residual densities as measured by Stand Density Index (70, 120, and 170 SDI), two levels of fertilization (fertilized and non-fertilized), and two levels of competition control (herbicide and non-herbicide). For each level of thinning, one plot would receive no fertilization and no competition control; one plot would receive fertilization only; one plot would receive competition control only; and one plot would receive both fertilization and competition control. Six control plots per site that received a standard every third row thin and no other silvicultural treatment were also established.

Residual trees were selected based on the following five criteria, in order of decreasing importance: (1) larger d.b.h., (2) stem form, (3) taller trees, (4) spatial distribution, and (5) crown quality. Selected densities for each plot were calculated using a modified form of Reineke's stand density index (SDI) equation (Zeide 1985):

$$SDI = N\left(\frac{D}{10}\right)^{1.7} \quad (1)$$

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

where, N = number of stems per acre, and D = quadratic mean diameter.

Thinning treatments were conducted in the fall of 1994, and all harvested trees were hauled to area mills. All residual trees in treatment plots were subsequently pruned during the winter of 1994-95 to a height of 25 feet. During the following summer, (1995) each tree was numbered and remeasured. Plots that received competition control were treated by hand spraying of herbicides during the fall of 1995. Herbicide application consisted of a mixture of Arsenol AC, Garlon 4, Red River 90, and surfactant totaling approximately 30 gallons per acre for application. Hardwood trees and shrubs greater than 2 inches in diameter were also "hacked and squirted". In the spring of 1996, fertilization plots were treated with a combination of urea and diamonium phosphate (DAP) giving a blended analysis of 29-17-0. Fertilizer was applied with shoulder mount hand crank spreaders at a rate of 563 pounds per acre. Plots were remeasured during the summers of 1996 and 1998, 2000, and 2002. Individual tree numbers applied during the 1995 measurement cycle allowed tree by tree tracking of increment through 2002.

RESULTS AND DISCUSSION

Pre and post thinning density attributes are shown in table 1. At the 2002 measurement cycle, average diameters ranged from the 8-to 12-inch class and from the high-to low-density classes for both study sites (table 2). For both sites the average diameter increased with decreasing density. Average total tree height ranged from 60 to 67 feet across both sites, with site 1 maintaining consistently taller trees. Within sites, tree heights were within 1 foot of each other with the exception of the control plots.

Growth data were analyzed to determine effect of thinning, fertilization, and competition control on average annual d.b.h. (inches per year) and basal area (square feet per acre per year) increment over the 8-year period from 1995 to 2002. Treatments were tested separately for site 1 and 2 using ANOVA (table 3):

$$Y_{ijkn} = \mu+\alpha_i+\beta_j+\delta_k+(\alpha\beta)_{ij}+(\alpha\delta)_{ik}+(\beta\delta)_{jk}+(\alpha\beta\delta)_{ijk}+\varepsilon_{ijkn} \quad (2)$$

where,

Yijkn = the observed plot increment for the (i,j,k) treatment and nth replication, n = 1,2,3;

Table 1—Density attributes at plot establishment (1994) and post-thin (1995) for study sites 1 and 2

Site	Density class	Density level	Stand density index	Basal area	Stems
				ft² per acre	*trees per acre*
1	Pre-treatment		346.3	166.6	710.5
	Low	1	74.0	35.8	103.7
	Medium	2	121.5	60.1	198.3
	High	3	171.6	83.7	300.0
	Control	4	231.5	111.8	463.3
2	Pre-treatment		274.2	132.4	550.9
	Low	1	74.4	35.8	105.3
	Medium	2	126.8	60.6	190.3
	High	3	176.3	84.2	290.0
	Control	4	196.0	95.1	381.3

Table 2—Average plot attributes by density level for sites 1 and 2 at 2002 measurement

Site	Density level	D.b.h.	Total height	Basal area
		inches	*feet*	*ft² per acre*
1	1	11.9	67.5	73.9
	2	10.2	68.0	106.2
	3	9.2	67.6	128.5
	4	7.9	62.7	142.7
2	1	12.3	63.0	80.1
	2	10.6	63.5	102.2
	3	9.5	63.8	128.5
	4	8.2	60.4	132.6

Table 3—*P*-values associated with the main effects from model (2) for sites 1 and 2

Site	Cultural treatment	*P*-values	
		D.b.h. increment	BA increment
		inches/year	*ft²/acre/year*
1	Thinning	0.000	0.028
	Fertilization	0.338	0.767
	Comp control	0.658	0.957
2	Thinning	0.000	0.735
	Fertilization	0.194	0.001
	Comp control	0.596	0.818

μ = the true mean of the population;

α i = the effect of the ith thinning treatment, i = 1,2,3;

β j = the effect of the jth fertilization treatment, j = 1,2;

δ k = the effect of the kth competition control treatment, k = 1,2;

( ) = 2- and 3-way interactions between the ith, jth, and kth treatments; and

ε ijkn = error term.

ANOVA indicated significant (α = 0.05) thinning and fertilization effects for diameter increment on both sites 1 and 2. The only other significant difference detected was for the fertilization effect on basal area increment on site 2. No significant two- or three-factor interactions were detected.

For significant treatment effects, one-way ANOVA was used to test for differences in average annual diameter and basal area increment between thinning, fertilization, and competition control treatments for sites 1 and 2. Table 4 indicates cases in which significant differences were detected between increments by site and thinning treatment. The Ryan-Einot-Gabriel-Welch's Multiple Range Test (REGWQ) was used for means separation. REGWQ is used to control the type I experimentwise error rate, while also effectively controlling type II error rates when testing pairwise comparisons (SAS 1989). In addition, REGWQ is more likely to discriminate between nontransitive results, which can frequently occur in multiple comparisons.

Table 5 indicates cases in which significant differences were detected between increments by site and fertilization or competition control treatments. Control plots (thinning density code = 4) were not included in these tests.

D.b.h. Increment

Significant differences were detected between each of the thinning treatments at both sites (table 4). D.b.h. increment was lowest for the highest density control plots and increased with decreasing residual density. Annual growth rates ranged from 0.22 inches per year for controls on site 1 to 0.61 inches per year for thinning treatment 1 on site 1. No significant treatment effects for fertilization and competition control were detected (table 5). However, on both sites the average annual d.b.h. increment was greater for plots that received the treatments than those that did not. Plots of the average d.b.h. and d.b.h. increment by measurement year and cultural treatment also indicate greater response associated with lower residual stand densities along with fertilizer and herbicide application (figs. 1 and 2).

For each thinning treatment, lower residual densities resulted in greater d.b.h. increment. This relationship is attributable to two factors: increased allocation resources to fewer trees as density decreases and the selection of superior trees at the time of plot establishment.

Table 4—Average diameter and diameter increment by site and density level between 1995 and 1998

Site	Density class	D.b.h.[a]	Basal area
		- - - standard error - - -	
1	1	0.56a	5.12ab
		(0.01)	(0.36)
	2	0.38b	6.39a
		(0.01)	(0.35)
	3	0.28c	6.14a
		(0.01)	(0.31)
	4	0.22d	4.42b
		(0.01)	(0.36)
2	1	0.61a	5.98
		(0.02)	(0.44)
	2	0.41b	5.39
		(0.02)	(0.78)
	3	0.30c	5.74
		(0.01)	(0.31)
	4	0.24d	5.35
		(0.01)	(0.44)

[a] Means with the same letter within a site are not significantly different using the REGWQ method on all pairwise comparisons.

Table 5—Average annual d.b.h. and basal area increment by cultural treatment for sites 1 and 2. Standard errors are listed below the means in parentheses

		Cultural treatment			
Site	Attribute	Fert[a]	No fert	Comp control	No comp control
1	D.b.h.	0.43	0.39	0.41	0.40
		(0.03)	(0.03)	(0.03)	(0.03)
	BA	5.82	5.95	5.90	5.87
		(0.36)	(0.24)	(0.28)	(0.32)
2	D.b.h.	0.47	0.41	0.45	0.43
		(0.03)	(0.03)	(0.04)	(0.03)
	BA	4.76 a	6.65 b	5.63	5.78
		(0.52)	(0.14)	(0.50)	(0.38)

D.b.h. = diameter increment at breast height (inches per year); BA = basal area increment (square feet per acre per year).

[a] Like letters within the same stand and cultural treatment show no significant difference using Fisher's LSD test at the α = 0.05 level.

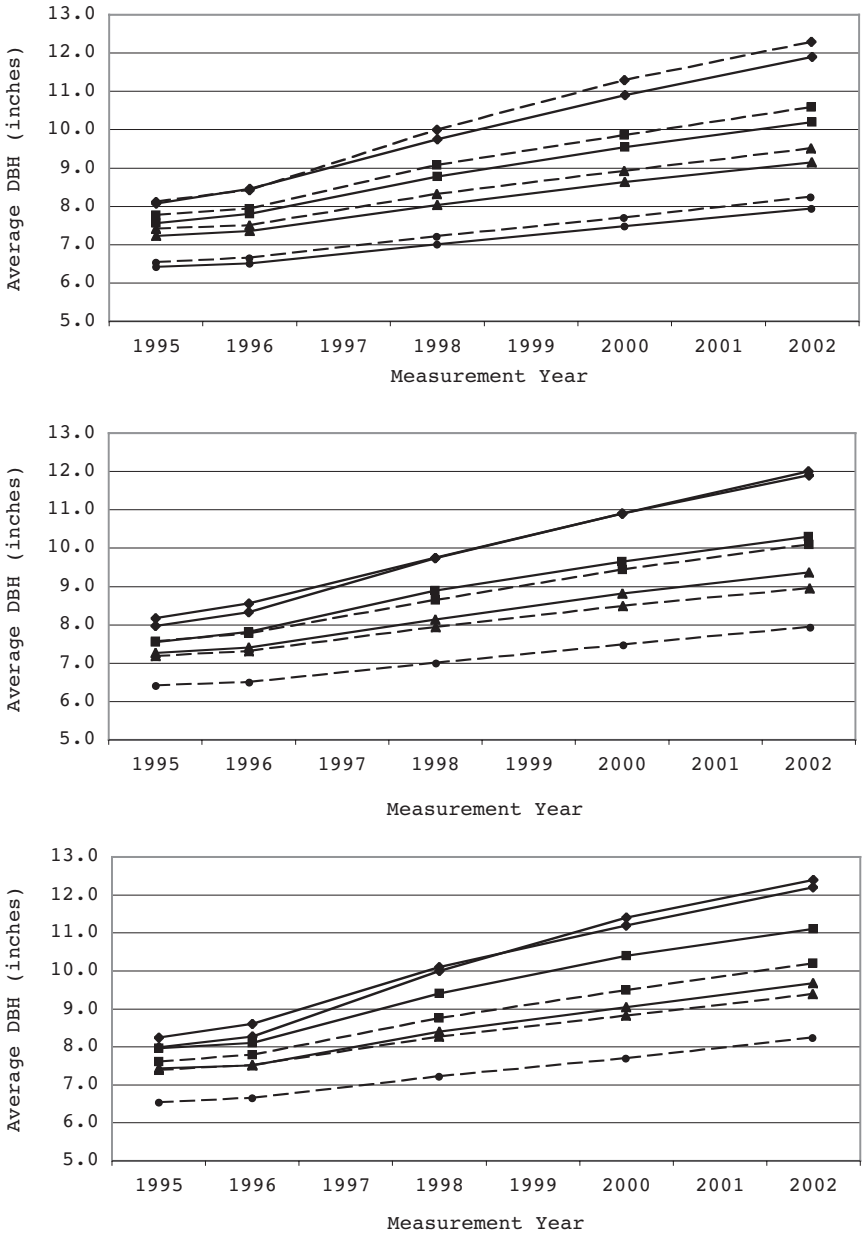

Figure 1—(top) Average d.b.h. plotted against measurement year by study site (Site 1 = solid line and Site 2 = dashed line) and density thinning treatment; (middle) average d.b.h. plotted against measurement year by fertilization treatment (fertilized = solid line and not fertilized = dashed line) and thinning treatment for Site 1; and (bottom) average d.b.h. plotted against measurement year by fertilization treatment and thinning treatment for Site 2. (◆ = density 1, ■ = density 2, ▲ = density 3, and ● = density 4).

Basal Area Increment

A significant difference was detected between thinning treatments for site 1 (table 5). Control plots (thinning treatment 4), which contained the highest residual density and had the lowest average annual basal area increment (4.42 square feet per acre per year), were not significantly different than thinning treatment 1 (5.12 square feet per acre per year), which had the lowest residual density. Also, no significant differences were detected between thinning treatments 1 through 3. Although thinning treatment 2 and 3 were significantly different from treatment 4, no difference was detected between treatment 1 and 4. This non-transitive effect could be the result of slow growth due to over-crowding in the highest density control plots and the low number of trees in the lowest density plots. Thus, although the lowest density class has greater diameter growth, it is putting that growth on so few trees that it is not contributing greatly to the overall basal area per acre. Consequently, the means are not separating from the other density classes.

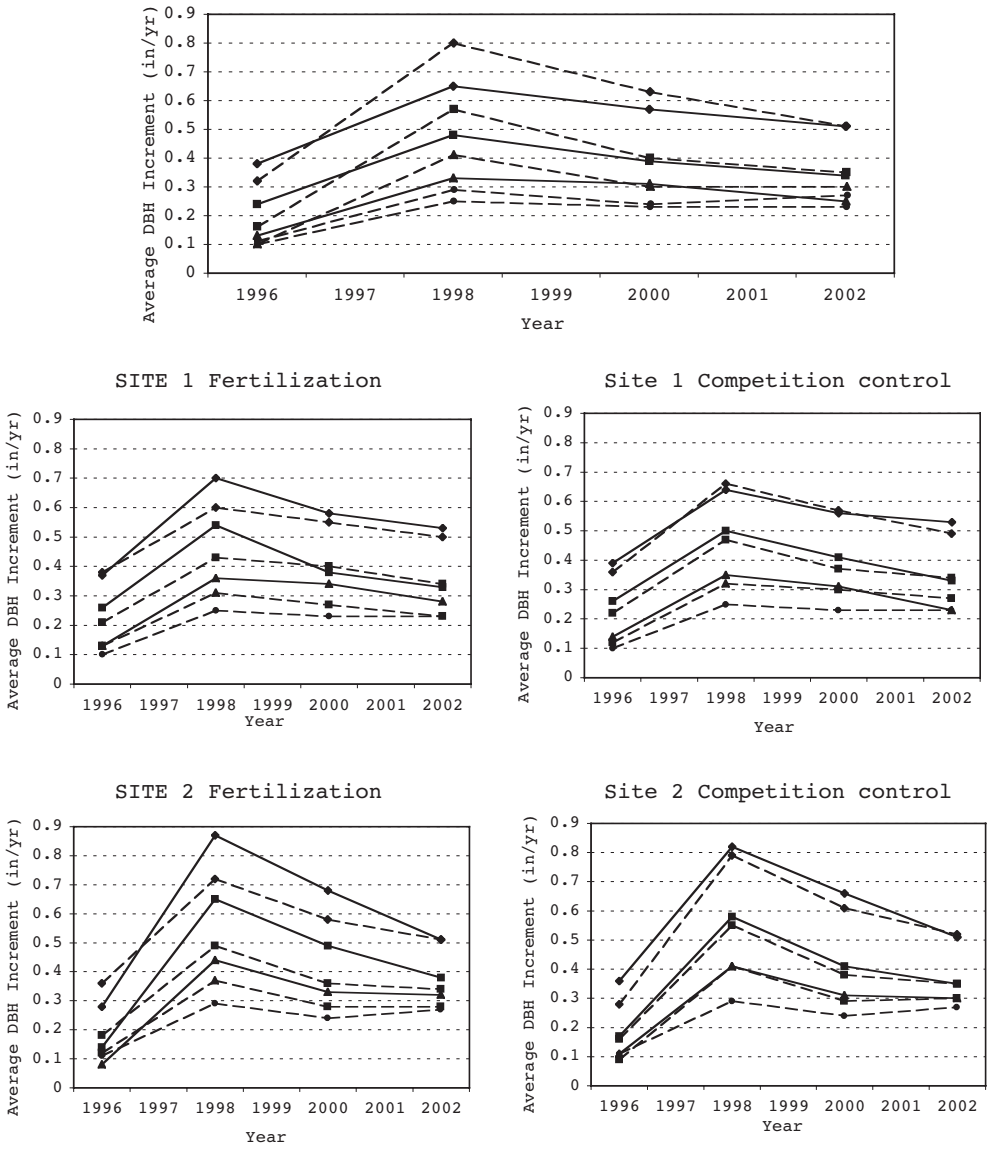

Figure 2—(top) Average d.b.h. increment plotted against measurement year by study site (Site 1 = solid line and Site 2 = dashed line); (middle) average d.b.h. increment for fertilization treatment (fertilized = solid line and not fertilized = dashed line) and competition control treatment (competition control = solid line and no competition control = dashed line), respectively, for Site 1; and (bottom) average d.b.h. increment for fertilization treatment (fertilized = solid line and not fertilized = dashed line) and competition control treatment (competition control = solid line and no competition control = dashed line), respectively, for Site 2. (◆ = density 1, ■ = density 2, ▲ = density 3, and ● = density 4).

A significant difference was detected for the fertilization treatment at site 2. Plots that received fertilizer had significantly lower basal area growth. Although not under the general scope of this paper, the lower basal area growth could be associated with higher than expected mortality associated with the fertilization treatment. Plots of average basal area and basal area increment by measurement year also depict the observed responses associated with cultural treatments (figs. 3 and 4). Note that basal area increment has been increasing or remaining steady for all thinning treatments at site 1, while increasing to a maximum (8 to 10 square feet per acre per year) in 1998 (4 years after treatment) and then sharply decreasing (2 to 5 square feet per acre per year) at site 2.

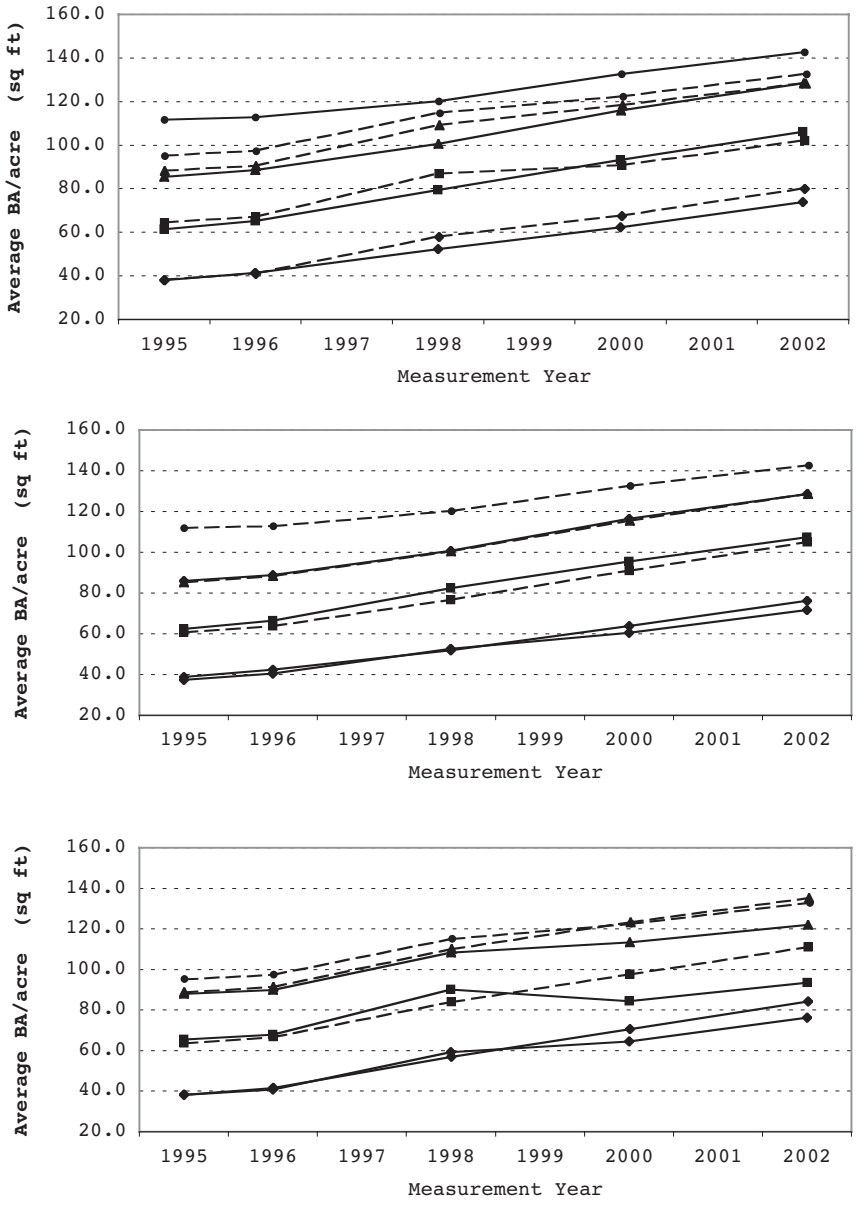

Figure 3—(top) Average basal area per acre plotted against measurement year by study site (Site 1 = solid line and Site 2 = dashed line) and density thinning treatment; (middle) average basal area per acre plotted against measurement year by fertilization treatment (fertilized = solid line and not fertilized = dashed line) and thinning treatment for Site 1; and (bottom) average basal area per acre plotted against measurement year by fertilization treatment and thinning treatment for Site 2. (◆ = density 1, ■ = density 2, ▲ = density 3, and ● = density 4).

ACKNOWLEDGMENTS

We wish to express appreciation to Temple Inland Forest Products Corporation for providing funding and study sites. We specifically thank Bill Stansfield for his continuing support during this study, and student field crews from Stephen F. Austin State University and Oklahoma State University for data collection.

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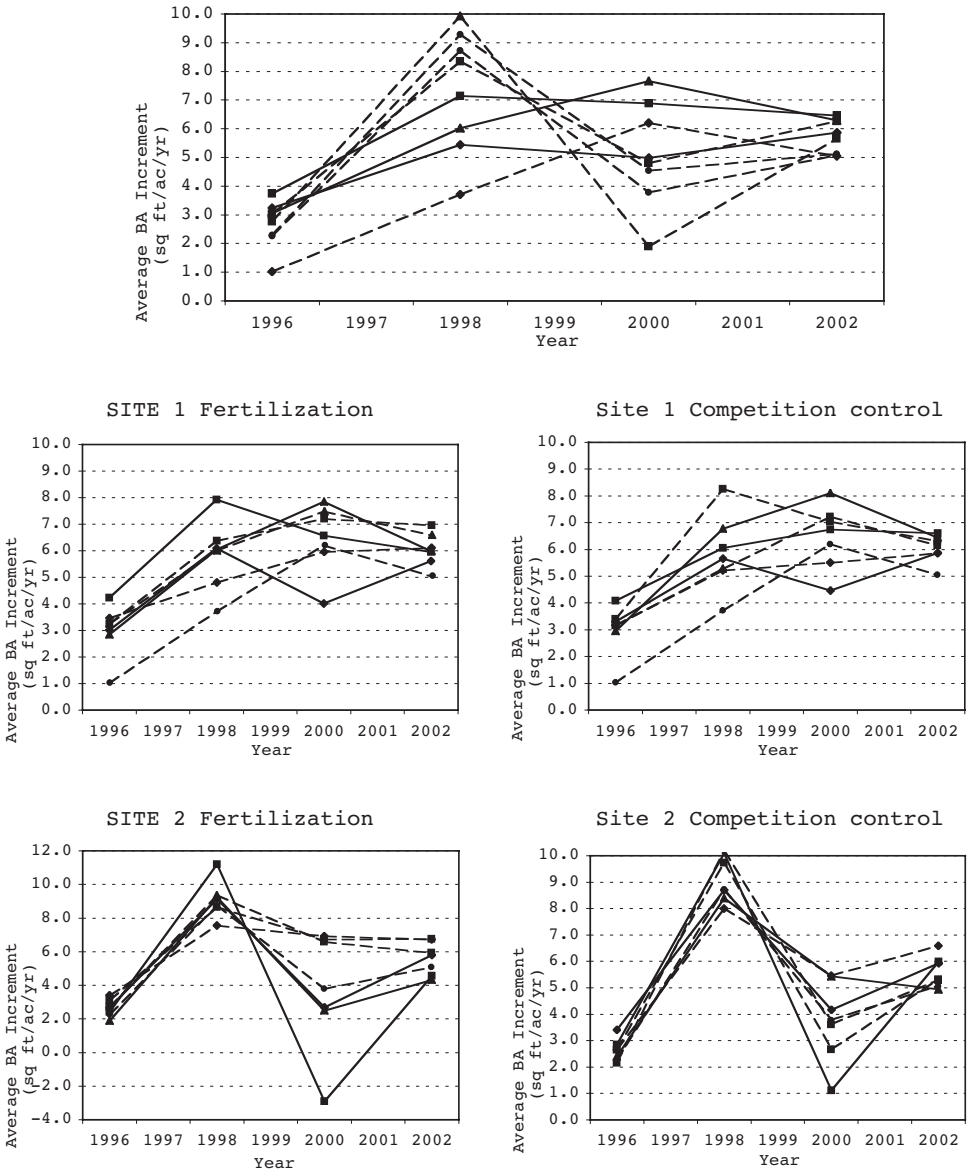

Figure 4—(top) Average basal area increment plotted against measurement year by study site (Site 1 = solid line and Site 2 = dashed line); (middle) average basal area increment for fertilization treatment (fertilized = solid line and not fertilized = dashed line) and competition control treatment (competition control = solid line and no competition control = dashed line), respectively, for Site 1; and (bottom) average basal area increment for fertilization treatment (fertilized = solid line and not fertilized = dashed line) and competition control treatment (competition control = solid line and no competition control = dashed line), respectively, for Site 2. (◆ = density 1, ■ = density 2, ▲ = density 3, and ● = density 4).

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SPOT APPLICATION OF DIAMMONIUM PHOSPHATE AND POULTRY LITTER AT ESTABLISHMENT IN AN OLD-FIELD PLANTED LOBLOLLY PINE PLANTATION

Bryan C. McElvany, E. David Dickens, and Tucker Price[1]

Abstract—A study area was installed in the Coastal Plain (Quitman County) of Georgia to determine the benefits of surface microsite application of diammonium phosphate (DAP) and poultry litter to planted loblolly pine (*Pinus taeda* L.) seedlings on an old-field site. Soils were Bonneau and Orangeburg. Experimental design was complete block with 3 replications per treatment. Treatments were: (1) control = no treatment, (2) spot surface application of DAP ($4.6x10^{-3}$ pounds per square foot) and (3) poultry litter ($6.9x10^{-2}$ pounds per square foot), (4) banded herbicide only, (5) DAP+herbicide and (6) poultry litter+herbicide. Loblolly pine groundline diameter (GLD), total height, and soil pH, P, K, Ca, Mg, Cu, Zn, and Mn at time of application were not significantly different. Two-year GLD, total height, and volume index (GLD^2 x height) for the three treatments with an herbicide component were significantly larger than the three treatments without an herbicide component. Two-year measurement parameter (GLD, total height, and volume index) results illustrate that there were no statistically significant benefits to adding DAP or poultry litter alone to the microsite around each seedling on this relatively fertile old-field site.

INTRODUCTION

Georgia's forest and poultry industries are two of the largest industries in the State, contributing an estimated 26 billion dollars to the annual economy and directly employing 175,000 workers (GASS 1998). Diammonium phosphate (DAP) is a common fertilizer used for pine establishment to provide N and P needs. Poultry litter can be utilized as an alternative to DAP during pine establishment. Many nonindustrial private forest landowners (NIPFLs) are interested in enhancing early growth of planted southern pines on old-field sites with the use of herbicides, inorganic fertilizers, and animal manures. Some NIPFLs have farm labor that can spot apply various fertilizer materials around each seedling. The objective of this study was to determine the benefits of a surface microsite (4 square feet) application of DAP and poultry litter in conjunction with herbicide to planted loblolly pine (*Pinus taeda* L.) seedlings on an old-field site.

METHODS

The study area was located in Quitman County, GA, on a relatively fertile former peanut field planted to a loblolly pine plantation in December 1999. The soils present on this old-field were Bonneau (Arenic Paleudults) and Orangeburg (Typic Kandiudults). Experimental design was complete block with three replications of six treatments. Treatments included (1) control or no treatment, (2) fertilization with DAP on a 4-square-foot area around each seedling at a rate of $4.6x10^{-3}$ pounds per square foot (equal to a broadcast rate of 200 pounds DAP per acre), (3) fertilization with poultry litter on a 4-square-foot area around each seedling at a rate of $6.9x10^{-2}$ pounds per square foot (equal to a broadcast rate of 1.5 tons per acre), (4) banded (4 foot) herbicide application of Oust (3 ounces acre per acre) and Atrazine (5 pints per acre), (5) DAP application in conjunction with herbicide, and (6) poultry litter application in conjunction with herbicide. The per-square-foot spot application level of DAP and poultry litter around each seedling was equivalent to the recommended DAP (200 pounds per acre, NCSUFNC 1998) and poultry litter (1.5 tons per acre, Dickens and others 2003) broadcast rate at planting for loblolly pine.

Individual plots consisted of 2 rows of 20 living seedlings at time of treatments. Two rows of untreated buffer seedlings were between each plot. Seedlings were measured each winter (survival, groundline diameter, and total height) and soil (0 to 6 inches) and foliage samples were collected. Data were subjected to a one-way analysis of variance, and all statistical tests were conducted at the $\alpha = 0.05$ significance level.

Poultry litter (table 1) and DAP were applied using a 5-gallon plastic bucket and calibrated cup on 5 and 10 April 2000, respectively. The herbicides were band applied by tractor-mounted tank sprayer and band applicator 15 May 2000.

RESULTS

Soil (table 2) and foliar (table 3) nutrient levels were generally above the minimum guidelines range for loblolly pine (Allen 1987, Pritchett and Comerford 1983, Wells and others 1973) 1 and 2 years after treatment (YAT) across the treatments. There were no treatment significant differences for P, K, Ca, Mg, Zn, or Mn in the surface soil or in foliar N, P, K, Ca, or Mg concentration 1 or 2 YAT.

First-and second-year seedling survival between treatments was not significantly different between treatments. Two-year survival ranged from 77 percent (poultry litter) to 92 percent (DAP). Two-year GLD and total height for those treatments with an herbicide component (poultry litter + herbicide, DAP + herbicide, and herbicide alone) were

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Table 1—Poultry (stacked broiler litter) litter characteristics and application level from a 1.5 tons per acre equivalent spot application to an old-field loblolly pine plantation at stand establishment in Quitman County, GA

Component	Concentration	Application level	
	percent	*pounds per acre*	*pounds per seedling (4 square feet)*
Total-N	4.25	127.50	0.0117
NH4-N	0.37	11.22	0.0010
Organic-N	3.83	114.90	0.0106
available-N	2.08	62.40	0.0057
P_2O_5	4.76	142.95	0.0131
K_2O	2.93	87.90	0.0081
Ca	2.72	81.60	0.0075
Mg	0.48	14.43	0.0013
S	0.52	15.75	0.0014
Cu	0.04	2.21	0.0002
Zn	0.04	1.05	0.0001

Available-N = 60 percent of organic-N and ammonium-N is estimated to plant available when surface applied in the first growing season.

Table 2—Soil nutrient status prior to treatment (2000) and 2 years after treatment (2002) in an old-field planted loblolly pine stand located in Quitman County, GA

Treatment	Phosphorus		Potassium		Calcium		Magnesium		Zinc		Manganese		pH	
	2000	2002	2000	2002	2000	2002	2000	2002	2000	2002	2000	2002	2000	2002
	pounds per acre													
P	45	40	89	68	692	524	33	38	2.7	2.0	27	27	6.3	6.3
P+H	45	43	81	68	659	566	30	30	2.0	2.0	27	33	6.4	6.3
C	55	43	96	75	600	436	30	35	2.7	2.0	28	31	6.2	6.3
H	56	48	85	67	516	392	32	32	2.7	2.3	25	32	6.2	6.2
DAP	51	44	101	74	736	475	38	35	2.7	2.0	27	30	6.3	6.4
DAP+H	41	38	91	56	522	396	33	26	2.0	2.0	25	33	6.3	6.3

P = poultry litter; P+H = poultry litter plus herbicide; C = control; H = herbicide only; DAP = diammonium phosphate fertilization; DAP+H = diammonium phosphate fertilization plus herbicide.

Table 3—Foliar nutrient status 1 year (2001) and 2 years (2002) after treatment on an old-field loblolly pine stand established in 2000 in Quitman County, GA

Treatment	Nitrogen		Phosphorus		Potassium		Calcium		Magnesium		Sulfur	
	2001	2002	2001	2002	2001	2002	2001	2002	2001	2002	2001	2002
	percent											
P	2.00	1.52	0.16	0.13	0.44	0.46	0.41	0.28	0.05	0.06	0.19b	0.15
P+H	1.93	1.47	0.15	0.14	0.42	0.45	0.44	0.26	0.05	0.05	0.18b	0.15
C	2.11	1.59	0.15	0.13	0.41	0.43	0.33	0.27	0.05	0.05	0.19b	0.15
H	2.00	1.56	0.16	0.12	0.44	0.44	0.37	0.25	0.06	0.05	0.20ab	0.14
DAP	2.21	1.57	0.16	0.12	0.44	0.39	0.36	0.24	0.05	0.05	0.22a	0.15
DAP+H	2.07	1.57	0.16	0.14	0.43	0.45	0.42	0.27	0.05	0.05	0.20ab	0.14

P = poultry litter; P+H = poultry litter plus herbicide; C = control; H = herbicide only; DAP = diammonium phosphate fertilization; DAP+H = diammonium phosphate fertilization plus herbicide.

Table 4—Pretreatment (2000), 1 year (2001), and 2 year (2002) posttreatment growth parameter means in an old-field planted loblolly pine plantation in Quitman County, GA

Treatment	Groundline diameter			Total height			Volume index		
	2000	2001	2002	2000	2001	2002	2000	2001	2002
	inches						*cubic inches*		
P	0.19	0.336b	1.086c	11.3	15.7c	49.4b	0.44	2.05b	66.34c
P+H	0.18	0.455a	1.488a	12.2	17.8ab	63.3a	0.44	4.18	152.20a
C	0.19	0.377b	1.284b	11.7	17.2abc	54.7b	0.44	2.77b	104.81bc
H	0.18	0.492a	1.584a	11.7	18.3a	65.6a	0.40	5.24a	185.63a
DAP	0.18	0.361b	1.276b	11.5	16.3bc	54.8b	0.39	2.54b	103.10bc
DAP+H	0.19	0.494a	1.512a	11.6	18.2a	60.6a	0.43	5.12a	162.48ab
p-value	0.756	< 0.0001	0.0008	0.749	0.035	0.005	0.855	0.0002	0.0025

P = poultry litter, P+H = poultry litter plus herbicide, C = control, H = herbicide only, DAP = diammonium phosphate fertilization, DAP+H = diammonium phosphate fertilization plus herbicide.

significantly greater than the treatments lacking an herbicide component (DAP, poultry litter, and control). Two-year volume index followed the same trend as GLD and total height (table 4). Two-year measurement parameters (GLD, total height, and volume index) results illustrated that there were no statistically significant benefits to adding DAP or poultry litter alone to the microsite around each seedling on this relatively fertile old-field site.

DISCUSSION

These research data suggest that controlling competitive vegetation is more beneficial than spot application of diammonium phosphate or poultry litter to loblolly seedlings at establishment on old-field sites with relatively high fertility. Application of a fertilizer treatment alone appears to increase competing vegetation, and, in this case, significantly decreased seedling early growth. If a landowner chooses to fertilize seedlings at establishment, then controlling the resulting unwanted vegetation must be considered to minimize competition.

The findings from this old-field site using spot application of DAP and poultry litter around seedlings with and without herbicides are different from those reported by Bush and others (1998) and Wilhoit and others (1998) where DAP and poultry litter were broadcast at planting with and without herbicides. Both studies found that loblolly pine early growth was significantly greater with poultry litter and herbicides than herbicides alone or no treatment. Their sites, however, were cutover, and soil nutrient status was likely much lower than the Quitman County, GA, old-field site.

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HOW ARE SHORT ROTATION WOODY CROPS AFFECTED BY INSTITUTIONAL FACTORS IN THE SOUTHERN UNITED STATES?

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Abstract—Short-rotation woody crops (SRWC) produce a variety of forest products useful to consumers such as pulp, energy biomass, and solid wood. The establishment and management of these crops before conversion into manufactured products are affected by several institutional factors. The first objective of this study was to identify and document institutional structures and programs that directly and indirectly affect a landowner's decision to establish SRWC. The second objective was to compare these factors affecting SRWC across states in the South. The methods used to achieve these objectives utilized library and Internet searches as well as telephone interviews and site visits with state tax experts, state forestry officials, industry representatives, and university researchers. Preliminary results are presented.

INTRODUCTION

Short-rotation woody crops (SRWC) are an alternative investment opportunity for landowners to produce a variety of forest products. One objective of this study was to identify and document existing tax structures, forestry regulations, and environmental issues that directly and indirectly affect short-rotation woody crops. A second objective was to compare institutional factors affecting SRWC across selected states in the South. The methods used included Internet and library searches of pertinent information. A validation process involved numerous telephone and field visits with experts.

FEDERAL TAXES

Landowners considering the establishment of SRWC are subject to federal and various state specific taxes depending on the location of their property. Despite similarities of SRWC in rotation length to Christmas trees, the Internal Revenue Service (IRS) treats SRWC as a timber resource for taxation purposes. For both nonindustrial and industrial landowners, land, equipment, and timber accounts must be created to track capitalized costs. Capitalized costs can only be recovered by those methods deemed acceptable for each account category. For instance, installation costs for land improvements such as access roads and water pumping stations have to be capitalized until the land is sold. Establishment costs for SRWC are placed in the timber account and not depleted until the timber is sold. The equipment costs can be depreciated over IRS specified life spans. For landowners interested in establishing SRWC on a smaller scale, the IRS does allow the amortization of establishment cost, excluding costs of installing irrigation systems, over an 8-year period. In addition, revenues generated from SRWCs face capital gains treatment as does any other timber crop. In general, taxation treatment of SRWC at the federal level is little different than for other timber crops.

STATE SPECIFIC TAXES

Nonindustrial and industrial landowners interested in establishing SRWC face a variety of state taxes. Typically, SRWC face common forestry taxes such as property or land-use taxes and severance taxes. Land-use taxes are applied at the county level where tax rates reflect the current land use. Tax rates for forest land use are generally lower than those for agricultural land use, except for places like the Mississippi Delta. Severance taxes are enforced by the State on all timber products severed from the landowner's property. Generally, this tax is paid by the severer, such as a logger, and the cost is passed on to the landowner through lower stumpage prices. In general, these state specific taxes are deductible for federal income tax purposes in the year in which they occur, according to IRS §164. The frequency and details of these state specific taxes can make certain locales more favorable for establishing SRWC. For instance, Idaho, Oregon, and Washington treat SRWC plantations as an agricultural land use and exempt them from state severance taxes. In the Southern United States, state governments treat SRWC plantations as a forest land use and subject them to severance taxes. States subjecting SRWC plantations to severance taxes include Alabama, Arkansas, Georgia, Louisiana, Mississippi, North Carolina, and South Carolina. Another important issue is whether irrigation equipment used in SRWC plantation establishment and cultivation is subject to taxation. Only Louisiana, Mississippi, and South Carolina do not subject irrigation equipment to taxation. Other states, such as Arkansas, Florida, Georgia, Louisiana, Kentucky, and North Carolina impose a form of tax on irrigation equipment.

FORESTRY REGULATIONS

A major issue that affects forestry regulations is the Clean Water Act of 1977. It authorizes the administrator of the Environmental Protection Agency (EPA) to issue federal and state agencies information pertaining to guidelines for identifying and evaluating the nature and extent of nonpoint sources of pollutants. In addition, it outlines processes,

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

procedures, and methods for controlling pollution stemming from non-point sources including silvicultural activities, which are relevant to SRWC. This has resulted in the development of voluntary and regulatory state best management practices to control pollution from forestry activities. In this study, most southern states utilize voluntary best management practices on forest land to comply with the Clean Water Act of 1977.

GENETICS AND TREE BREEDING

Many short rotation woody crops are heavily dependent on traditional tree breeding practices to develop trees with desirable attributes. In the Pacific Northwest, the most prevalent practice is cross-pollination, which is common for agricultural crops. Attributes that are desirable and commonly selected include those that improve tree vigor, height, and diameter. Other practices that are not typical include the use of molecular biology for obtaining desirable tree attributes. Planted trees which have attributes selected by molecular biology practices are considered genetically engineered (GE). In general, the development of new tree breeds allows landowners to produce more wood with desirable attributes on a per acre basis. In addition, SRWC establishment on agricultural lands leads to wildlife habitat diversification (Twedt and Portwood 1997).

Despite the benefits derived from traditional tree breeding programs, numerous environmental groups do not differentiate between trees derived from traditional or nontraditional breeding practices and lump them under the classification of genetically engineered. These groups believe that SRWC with GE trees are generally sterile environments, promote soil erosion, water pollution, gene escape, and degenerate soil productivity (Greenpeace 2000, WWF 1999). They use the terms “Frankentrees, “Frankenscience” and “Frankenforestry” to describe genetically engineered trees (AP 1999, Weiss 2000). Some of these groups have utilized terrorist tactics such as burning down research labs, vehicles, endangered species, and destroying genetically engineered crops and trees (Service 2001, Welch 2000). Groups claiming responsibility include “Reclaim the Genes,” “Genetix Goblins,” “Earth Liberation Front,” and “The Washington Tree Improvement Association” for activities in British Columbia, Oregon, and Washington (BAN 2000, Bernton 2001, ENS 1999, GA 2000, Tuttle 2000). According to Service (2001), from late 1999 to mid-2001, 16 attacks have been made against research facilities conducting genetic engineering of plants. Of these attacks, six focused specifically on species such as poplar used as SRWC resulting in millions of dollars in losses.

For landowners interested in establishing SRWC, it is important to focus on attacks by eco-terrorists on SRWC with genetically engineered trees and advocacy campaigns against genetically engineered plants. Attacks by eco-terrorists, although gaining publicity, have not affected large acreages of SRWC (Service 2001). There is a growing advocacy campaign against perceived genetically engineered plant products. Several food processing companies have had to remove genetically engineered food products from store shelves in Europe (Halweil 1999). A review of the literature and Internet sources does not reveal any large campaigns targeting genetically engineered wood; however, the environmental campaign against tree breeding may affect wood marketing.

SUMMARY

Landowners have to consider a wide variety of factors when considering the establishment of SRWC. Taxation is important because of the inherent impacts on investment returns from a per acre basis. In the South, SRWC are considered a forest land-use and are subject to federal and state timber tax rules. In addition, most southern states ask landowners to implement BMPs voluntarily to meet clean water regulations. Finally, SRWC landowners planting trees, developed by breeding programs, may face pressure from environmental groups, which result in an uncertain market for their fiber in the future.

ACKNOWLEDGMENTS

Approved for publication as Journal Article No. FO228 of the Forest and Wildlife Research Center, Mississippi State University. Our thanks is given to Drs. Keith L. Belli and Deborah A. Gaddis for constructive criticisms.

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Site Amelioration and Productivity

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EARLY GROWTH RESPONSE OF SLASH PINE TO DOUBLE-BEDDING ON A FLATWOODS SITE IN GEORGIA

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Abstract—A somewhat poorly-drained site in the Georgia flatwoods was prepared with single- and double-bedding and was planted with slash pine (*Pinus elliottii* Engelm.) seedlings in October. Half of the plots were treated with imazypyr in March. Double-bedding increased 7th year volume by 5 m^3 per ha, but due to insufficient control of gallberry [*Ilex glabra* (L.) Gray], the herbicide treatment did not significantly increase volume growth. A break-even economic analysis indicated that an increase of 19 m^3 per ha at age 20 years would be sufficient to justify the extra cost of double-bedding (stumpage value = $20 per m^3; 7 percent interest rate). A review of the literature indicated that single-bedding typically increased yield but did not consistently increase the probability of survival. Equations developed suggest that single-bedding may, on average, increase yields by 21 to 28 m^3 per ha.

INTRODUCTION

Early herbicide treatments can suppress competing vegetation in southern pine plantations leading to increased pine growth (Lauer and Glover 1998, Lauer and Zutter 2001, Miller and others 1995, NCSFNC 1996, Quicke and others 1996, Swindel and others 1988, Zutter and Miller 1998). This may lead some to conclude that herbicides always increase volume growth. However, a few studies have shown that some herbicide treatments might decrease pine growth (Lauer and Glover 1999, NCSFNC 1999, South and Mitchell 1999). On some sites, this is due to selective control of competing vegetation. In one study, the control of herbaceous vegetation allowed gallberry [*Ilex glabra* (L.) Gray] to colonize the site resulting in reduced pine growth (South and Mitchell 1999). Managers need to be aware of which species will be suppressed by the herbicide and which will be released to compete with the pines. A single herbicide application is not synonymous with total vegetation control.

Bedding is commonly practiced on poorly drained, lower Coastal Plain sites to improve drainage (Cain 1978), soil aeration (Dougherty and Gresham 1988, Morris and Lowery 1988), and to provide long-term control of competing woody shrubs (Lauer and Zutter 2001, Schultz 1976, Schultz and Wilhite 1974). When compared to herbaceous cover, shrub cover can be a greater competitor and resulted in greater reduction of pine growth (Lauer and Glover 1998, 1999; Zutter and Miller 1998). Double-bedding is currently practiced to improve bed quality and to increase the level of shrub control (Lauer and Zutter 2001). Double-bedding involves a first pass during the summer, and then a plow is run over the beds a second time several weeks prior to planting.

Lauer (2000, 2001), Lauer and Glover (1996), and Lauer and Zutter (2001) found that double-bedding increased early growth relative to single-bedding. These studies did not surpass age 5, and no long term studies have been published comparing single-bedding to double-bedding. All of these studies have used double-bedding treatments consistent with our definition of double-bedding.

The combination of double-bedding and early post-plant herbicide applications is an effective way to increase early growth. Double-bedding provides excellent control of shrubs and hardwoods (Lauer and Zutter 2001); however, the control of shrubs can result in an increase in herbaceous vegetation (Lauer and Glover 1995, Miller and others 1991, Zutter and Miller 1998). The treatments combined can provide early control of both herbaceous vegetation and shrubs and hardwoods (Lauer and Zutter 2001).

Researchers sometimes place too much emphasis on results from an arbitrary significance level. This is especially true when the power of the test is low (VanderSchaaf and others 2003, Zedaker and others 1993). In some cases, a treatment may be economically viable but due to site variations, volume gain is not statistically significant (resulting in a Type II error). Therefore, we conducted a break-even analysis to determine if the cost of treatments might result in a positive return on investment. This study was conducted to determine if double-bedding produced increases in pine growth relative to single bedding and if an interaction existed between bedding and herbicide treatment.

METHODS

The study was located on a somewhat poorly drained flatwoods site near Homerville, GA. The soil is within the Ocilla series and is a loamy, siliceous, thermic Aquic Arenic Paleudult (Shrock 1994). A pine plantation was clearcut in the spring of 1991, and the area was raked, piled, and burned in June 1991. Treatments included two levels of site preparation, single-bedding and double-bedding, and two levels of post-planting vegetation control, herbicide application or none. Treatments were arranged as a split-plot design (bedding as the main effect). The first bedding pass occurred in late June 1991 and the second in early October. Seedlings were machine planted October 16, 1991 by an operational crew on a 1.8 x 3.0 m spacing. A

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

band application of 105 g a.i. per ha of imazapyr was applied by an operational crew in March, 1992. No surfactant was used.

Diameter at breast height (d.b.h.) and height were measured in the winter of 1999. Individual tree volume was estimated using a formula developed by Van Deusen and others (1981). Percent survival, average d.b.h., arithmetic mean height (height), individual tree volume, and volume per ha were analyzed using Proc GLM. A break-even analysis (at 7 percent interest) was conducted to determine the amount of volume gain required to make a treatment economically feasible (Bentley and others 1984, Fox 1988). Costs for the single-bedding, double-bedding and imazapyr treatments were $90, $160, and $80 per ha, respectively.

The literature was surveyed and 46 reports involving single- or double-bedding treatments were reviewed, and data for survival, height, basal area, and volume were compiled www.forestry.auburn.edu/south/bedding.xls. Regression analyses were conducted to determine the general response of height (129 comparisons), survival (81 comparisons), and yield (50 comparisons) to single bedding.

RESULTS

Double-bedding at the Homerville site increased height by about 0.45 m but this increase was not significant ($\alpha = 0.10$). Double-bedding increased volume per ha while the imazapyr treatment resulted in no significant increase in growth (table 1). Although there was no statistical interaction between bedding and herbicide treatment, the combination of double-bedding and imazapyr (d.b.h.) produced 5.3 m^3 more volume per ha than the single-bed treatment (SB) (table 2). A break-even yield analysis indicated that by age 20, an additional 19 m^3 per ha would justify the cost of a double-bedding treatment.

When compared to non-bedded treatments, single bedding tended to increase height growth (fig. 1). In only one comparison did bedding reduce heights by more than 50 cm (Lennartz and McMinn 1973). Overall, single-bedding did not have a consistent effect on seedling survival (fig. 2). Out of 81 comparisons, only 7 bedding treatments were significantly different from the controls (4 were lower and 3 were greater than controls). Overall, single-bedding increased volume per ha (fig. 3). Out of 50 comparisons, 14 resulted in significant increases in yield. The equation predicts a yield increase of 21 and 28 m^3 per ha for non-bedded stands producing 100 to 200 m^3 per ha, respectively.

DISCUSSION

Unlike other studies (Lauer and Zutter 2001, Quicke and others 1996), we found no economic advantage of applying imazapyr to control herbaceous weeds on this site (table 2). This is because the initial control of herbaceous vegetation allowed gallberry to increase, eventually resulting in

Table 1—Probability of a greater *F*-statistic for seventh-year field survival (transformed) and arithmetic mean seventh-year height, arithmetic mean diameter at breast height (d.b.h.), and volume per tree and hectare of *Pinus elliottii* seedlings

Source	Survival	Height	d.b.h.	Volume per tree	Volume per ha
	- - - - - - - - - - - - - -		*P > F value*		- - - - - - - - - - - - - -
Replication	0.07	0.33	0.85	0.79	0.39
Bedding (B)	0.17	0.12	0.12	0.14	0.06
Herbicide (H)	0.87	0.83	0.92	0.86	0.94
Bedding X herbicide	0.72	0.56	0.76	0.57	0.48

Table 2—Effect of bedding and herbicide treatments on seventh-year survival, trees per ha, arithmetic mean height, arithmetic mean diameter at breast height, and volume per tree and hectare of *Pinus elliottii* seedlings

Treatment	Survival	TPH	Height	d.b.h.	Volume	Volume
	percent		*m*	*cm*	*m^3/tree*	*m^3/ha*
SB	64.4	1,154	5.5	9.5	0.015	17.7
SBH	63.4	1,137	5.3	9.4	0.014	16.3
DB	69.3	1,243	5.8	9.9	0.017	21.0
DBH	68.9	1,236	5.9	10.1	0.019	23.0

TPH = trees per ha; d.b.h. = diameter at breast height; SB = single-bed, no herbicide; SBH = single-bed, herbicide; DB = double-bed, no herbicide; DBH = double-bed, herbicide.

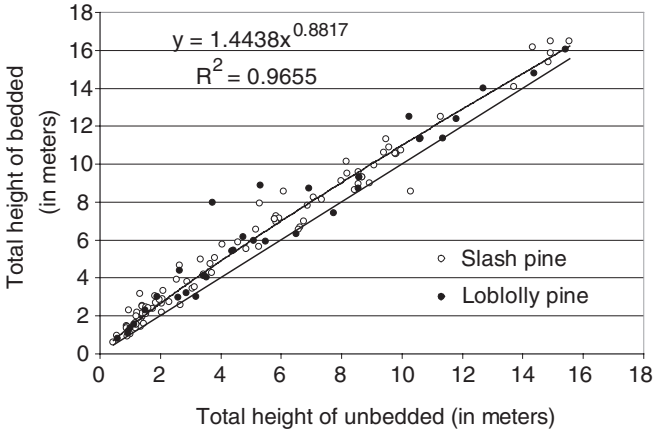

Figure 1—Height of single-bedded plots over height of unbedded plots from several studies conducted during the last 30 years. The solid line represents equal survival of the two treatments. The dashed line represents the regression equation (n = 129).

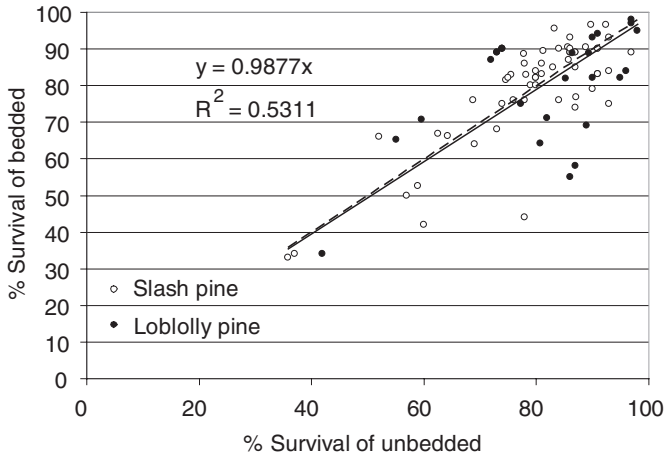

Figure 2—Survival of single-bedded plots over survival of unbedded plots from several studies conducted during the last 30 years. The solid line represents equal survival of the two treatments. The dashed line represents the regression equation (n = 81).

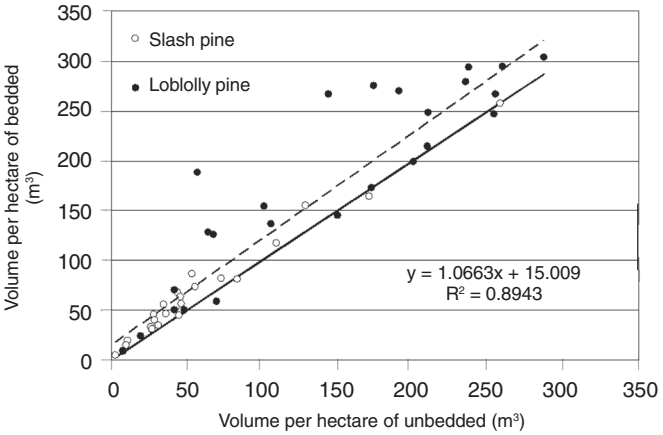

Figure 3—Volume per hectare of single-bedded plots over volume per hectare of unbedded plots from several studies conducted during the last 30 years. The solid line represents equal volume yield of the two treatments. The dashed line represents the regression equation (n = 50).

a decrease in pine growth (South and Mitchell 1999). The use of imazapyr alone may not be cost-effective if other site preparation techniques have not adequately controlled herbicide-resistant woody competitors. In order to be cost effective, the herbicide treatment would need to increase yield by approximately 22 m^3 per ha by age 20 years. However, by age 7 years, a gain of only 2 m^3 per ha occurred with the double-bedding treatment.

Although double-bedding on this site increased 7th year volumes relative to single-bedding, a forest economist would be more interested in answering the question: Will the investment in double-bedding be recouped at harvest? It should be kept in mind that currently pulpwood is worth about $9 per m^3 while chip-n-saw logs sell for about $36 per m^3. In our analysis, we used a value of $20 per m^3 (which assumes a mix of some chip-n-saw size trees with some pulpwood). If we assume a "Type C" response equal to a 1 year advance in stand development, we might expect to harvest an additional 20 m^3 per ha (assuming a site productivity of approximately 20 m^3 per ha per year). This amount of increase would justify the additional cost for double-bedding. Based on results from this study and from a previous publication (South and Mitchell 1999) at age 4 (single-bedding = 6.56 m^3 per ha, double-bedding = 8.59 m^3 per ha), it does not appear that a "Type C" 1 year advance is occurring. Based on these early results, the age-shift is much less than 1 year, leading to the conclusion that the yield returns from double-bedding on this site may not justify the investment.

It is necessary to determine when current annual increment (CAI) is greatest and whether to thin or to harvest near this age. If the stocking of a plantation is not properly managed following intensive site preparation (by conducting a commercial thinning), then the early gains from a "Type C" volume per ha response may be wasted. Other studies on eastern Coastal Plain soils have shown a Type B response following bedding (Dickens and others 1988, Gent and others 1986, Lennartz and McMinn 1973, Shiver and others 1990, Wilhite and Jones 1981). However, these studies are far from rotation age. It is imperative that managers continue to capture the early increase in growth caused by either single- or double-bedding. This can be achieved through either thinning or by harvesting.

In this study, the average root collar diameter (RCD) at time of planting was 7 mm across all treatment combinations. South and Mitchell (1999) found that seedlings of this size competed effectively with herbaceous weeds. The lack of response to herbicides on this site is likely a combination of both gallberry competition and the use of large planting stock. Perhaps planting morphologically improved seedlings alone on single-beds will result in as much or more growth than planting smaller sized seedlings on double-beds plus a March herbicide treatment.

REVIEW OF GROWTH RESPONSE TYPES

Several authors have described growth response types (Hughes and others 1979, Morris and Lowery 1988, Nilsson and Allen 2002). However, we feel there are some inconsistencies. When authors are discussing growth response types they should specify the variable with which

they are working (i.e. height growth or volume per ha). Second, rotation age is the only age at which growth response types are of any practical importance. If authors are discussing a growth type response for any other age, they should specify the age.

There are five "harvest-age" growth responses to silvicultural treatments (Morris and Lowery 1988, Nilsson and Allen 2002). A "Type A" response is when incremental volume growth (i.e. CAI) is greater on treated than untreated areas throughout the entire rotation. A "Type B" response occurs when early incremental volume growth is greater on the treated areas, but incremental volume growth at later ages is the same. A "Type C" response is when incremental volume growth on treated plots is greater early in the rotation, but at later ages, incremental volume growth declines so that yield becomes equal for treated and non-treated areas. A "Type D" response is when early incremental volume growth on treated areas is greater, but at later ages volume growth increment declines so that yield actually decreases in the treated area. A "Type E" response occurs when treated incremental volume growth is less than the untreated throughout the entire rotation.

Several studies suggest a Type B response for single-bedding (Beers and Bailey 1985; Cain 1978; Haywood 1980, 1983, 1987; Haywood and Tiarks 1995; NCSFNC 1996; Outcalt 1984; Sarigumba and Anderson 1979; Tiarks 1983), but a few sites appear to result in a Type A response (Gent and others 1986, NCSFNC 1996, Nilsson and Allen 2002). However, studies up to age 18 years are probably too young to make a definitive statement about the "harvest-age" volume response to bedding. Morris and Lowery (1988) concluded that a Type B response generally occurs on flatwoods sites with sandy surface soils and a Type A response generally occurs on fine textured-poorly drained mineral soils. They agreed with Dewit and Terry (1983) who concluded that these responses occurred on the flatwoods sites because early accelerated growth resulted from a short-term increase in organic matter decomposition and greater nutrient availability. On the fine textured soils, growth increase was largely due to improved aeration and water movement.

The amount and type of competing vegetation could also affect the type of response observed. Nilsson and Allen (2002) concluded that a Type B response is likely to occur if herbaceous vegetation is greatly reduced, but a Type A response could result if hardwood vegetation is eliminated. A Type A response may occur for single-bedded, and more often for double-bedded, sites since it is thought to provide long-term control of shrubs and hardwoods (Lauer and Zutter 2001). Several studies have shown that herbaceous production decreases with increases in pine basal area (Lewis 1989, Wolters 1973, Zutter and Miller 1998). On the other hand, shrub and hardwood production appear to be independent of pine basal area and develop with age similar to the pines (Zutter and Miller 1998). Since this is true and each site has a maximum carrying capacity for a particular age, after herbaceous vegetation has been shaded-out, a double-bedding treatment may produce a long-term Type A response. This could be due to better control of shrubs and hardwoods on double-bedded areas and the presence of large amounts of shrubs or hardwoods accounting for relatively more of the stand-level growth on unbedded or single-bedded sites. It is difficult to conclude that bedding will always result in a particular type response, because this is highly dependent on the species and amount of the competing vegetation, especially for shrubs and hardwoods.

CONCLUSION

This study provides insight into the advantages and disadvantages of particular site preparation treatments. Double-bedding appears to improve early volume growth per acre on flatwoods sites that contain gallberry. The verdict on long-term growth and economic return is still out. However, applying a single herbicide treatment to this site does not appear to be economically feasible. Pine growth may be reduced following selective herbicide treatments on sites containing thick-cuticled vegetation such as gallberry.

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RELATIONSHIP OF ABOVEGROUND BIOMASS PRODUCTION, SITE INDEX AND SOIL CHARACTERISTICS IN A LOBLOLLY PINE STAND

Minyi Zhou and Thomas J. Dean[1]

Abstract—As a part of the continuing studies of the Cooperative Research in Sustainable Silviculture and Soil Productivity (CRiSSSP), 24 experimental plots in a loblolly pine (*Pinus taeda* L.) stand have recently been installed near Natchitoches, LA. The plots were uniformly assigned to 3 blocks based on topography (i.e., up slope, midslope, and down slope). Trees and understory vegetation were sampled to determine total biomass production and nutrient content. Soil carbon, macronutrients, and mineralizable nitrogen were also analyzed. Stem analysis indicated that up-slope and midslope blocks had similar site indexes, 19 m and 18 m at base 25 years, respectively, and both had significantly higher site indexes than that of down-slope block (15 m). Major soil nutrients (N, K, Ca, and Mg) covaried with overall biomass production in the stand but not with the site index. However, mineralizable N was significantly and positively correlated with the site index ($R^2 = 0.24$, $p < 0.02$). Our results suggest that overall, soil nutrients alone are not a strong indicator of site quality. Mineralizable N, in contrast, may be a better measurement of overall quality of the stand on this particular soil.

INTRODUCTION

Concerns over the sustainability of intensive forest management practices led to the establishment of a nationwide study of long-term soil productivity (LTSP) by the U.S. Department of Agriculture, Forest Service, in 1989 (Powers and others 1990). The concerns also drew the attention of forest industries and universities and eventually lead to the Cooperative Research in Sustainable Silviculture and Soil Productivity (CRiSSSP) that initiated studies along the gulf coast in 1993 (Carter and others 1995). One of the principal objectives of CRiSSSP is to link soil properties to site productivity.

It is generally agreed that productivity is associated with soil fertility. In forestry, we expect higher productivity with higher site index. Fisher and Binkley (2000) state, "Site index is extremely important in site quality analysis in North America because it forms the standard against which all other forms of site evaluation are measured." Despite the limitation of site index, its usefulness in assessing site quality is widely accepted. Acknowledging or understanding the relationships among aboveground biomass production, site index, and soil properties of a current generation of trees could help us understand the potential productivity of the next generation of trees. This would also provide some insights on the dynamics of soil properties associated with stand development. In addition, these efforts may help to identify factors that affect the productivity of the site. Therefore, the objective of this study is to examine the relationships among aboveground biomass production, site index, and soil physical and chemical properties in a mature loblolly pine stand.

STUDY AREA AND METHODS

Study Area

This study was conducted on a 45- to 55-year-old, naturally regenerated loblolly pine (*Pinus taeda* L.) stand located in Natchitoches Parish (lat. 31.8°N, long. 93.0°W), LA owned by Roy O. Martin Timber Company. The site is 59 m above sea level, has a mean temperature in January and July of 7.9 and 28.6 °C, respectively, and receives an average of 1395 mm precipitation annually. The soil is primarily a fine-silty, siliceous, semiactive, thermic Glossaquic Paleudalf. It is a deep, moderately well-drained, and very slowly permeable soil that formed in loamy over clayey sediment of Tertiary Age. The soil is primarily Keithville series and some Shatta series. Three blocks were installed on a topographical gradient. Up-slope and midslope blocks were established on the side of a gentle slope, and a down-slope block was established at the toe of the slope. General information of pine trees associated with each topographical position is given in table 1. There might have been cultivation on this site some time in the past.

Biomass Assessment

Within each slope position, aboveground biomass and soil properties were measured within eight 42-by 35-m plots. The biomass was determined by various components for each plot. Biomass of the overstory trees [> 5 cm in diameter at breast height (d.b.h., 1.37 m)] were determined with measurements of all d.b.h. and total height and then calculated with equations developed by Clark and others (1985) for hardwoods and Baldwin (1987) for pine trees. Understory and litter biomass were determined with 4 clipped-plots, each of which was 1 by 2 m in size and systematically placed in the middle of each quadrant within

Table 1—General information on pine trees for each topographical position of a loblolly pine stand near Natchitoches, LA

Slope position	Up-slope	Mid-slope	Down-slope
Number (*per ha*)	71	65	148
Relative frequency (*%*)	56	56	61
Basal area (m^2 *per ha*)	8.8	5.9	11.0

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

a plot. All plant samples were dried at approximately 65 °C to a constant weight and ground to pass a 20-mesh stainless steel screen. Nutrient contents of the various biomass components were determined. Total nitrogen (N) and carbon (C) were measured with a Fison's Instrument Model EA 1108 CHN Analyzer. For other elements, samples were wet-ashed in nitric acid-hydrogen peroxide (Huang and Schulte 1985) and analyzed with an ICP emission spectrophotometer. Height development of the existing stand was reconstructed with ring counts on wood disks cut at fixed height intervals along the stem. Average total height at 25 years old for the dominant or codominant trees sampled in each slope position was taken as site index.

Soil Properties

Soil bulk density was determined for 3 depths at 5 locations in each plot using a volumetric probe with a 5.0-cm inside diameter. Soil samples were taken at depths of 0 to 5, 10 to 15, and 20 to 25 cm and dried at 105 °C to a constant weight.

Soil samples were collected at 4 random locations in each plot for nutrient analyses. These soil samples were taken to a depth of 30 cm from the soil surface. Soil samples were mixed, air-dried, and sieved to pass a 2-mm screen. For exchangeable cations, 2.5 g of soil were placed in 25 ml of 1.0 M NH_4OAc (pH 7.0), shaken for 15 minutes, filtered, and analyzed in ICP emission spectrophotometer. Soil nutrients were determined with methods similar to those used to measure nutrient concentration in the vegetation.

Soil N availability

An index of potentially mineralizable N was estimated using an anaerobic N mineralization technique described by Waring and Bremner (1964) and by Keeney (1982) with modifications. Soil samples were collected in July 2000 at a depth of 20 cm with a push-tube probe (2.0 cm inside diameter), sealed in plastic bags, and put on ice for storage and transport. Ten grams of soil were incubated in a 120-ml plastic bottle with 20 ml of deionized water. Oxygen in the bottle's head space was flushed with nitrogen gas for approximately 10 seconds and capped tight immediately. Samples were incubated at 40 °C for 7 days. Dry weight of the sample was determined with a 20-g subsample. Immediately after incubation, mineral N was extracted in a 100-ml solution of 2-N KCl shaken for 1 hour at 225 rpm. After settling, the mixture was vacuum filtered and the filtrate refrigerated until analysis. Ammonium concentration of the filtrate was determined with a precision conductivity cell (Timberline Instruments). Standard curves were developed with eight diammonium sulfate solutions. Available mineral N per ha was calculated with corresponding soil bulk density at a 0- to 30-cm depth.

Statistical Analysis

Data were summarized by plot and analyzed by slope position. Therefore, eight data points per slope position were used in the analysis of variance and regression analysis for biomass, site index, soil bulk density, and mineralizable N. Other soil nutrient contents were calculated by averages of nutrient concentration and soil bulk density of each slope position. Unless indicated otherwise, all significant difference refers to $\alpha = 0.10$.

RESULTS AND DISCUSSION

Standing biomass for the various components within each slope position is listed in table 2. Pine biomass in midslope block was lower than the pine biomass in up-slope and down-slope blocks, though not significantly lower. Hardwood biomass was three times or more higher in the down-slope block than in the up-slope and midslope blocks. Understory and litter biomass systematically declined from the up-slope to the down-slope block. Total aboveground biomass was highest in down-slope block and lowest in midslope block. The comparatively low total biomass in the midslope block was most likely due to low pine density, whereas the comparatively high total biomass in the down-slope block had the highest density of pine trees (table 1). These differences in biomass components clearly indicate that block to block variations exist within this study site.

The site indexes of the up-slope and midslope blocks were similar, 19 and 18 m, respectively. Site indexes from these topographic positions were about 23 percent higher than the down-slope position's site index of 15 m (fig. 1). This suggested a gradient in site quality from up-slope to down-slope blocks.

Table 2—Aboveground biomass (Mg/ha) of each topographical position from a loblolly pine stand near Natchitoches, LA[a]

Slope position	Up-slope	Mid-slope	Down-slope
Component			
Pine	67.2a	43.4a	62.9a
Hardwood	5.9b	9.3b	33.1a
Understory	14.3a	9.2ab	6.1b
Litter	18.8a	16.2b	14.7b
Total	106.2ab	78.1b	116.8a

Within each component, same letters indicate no significant difference among slope positions at $\alpha = 0.10$ level.

[a] Stand age was averaged at 50 years.

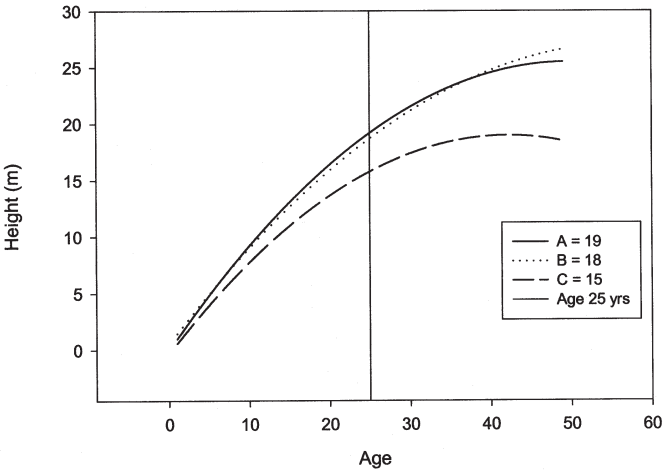

Figure 1—Growth curves reconstructed from stem analysis of dominant and codominant trees of each slope position in a loblolly pine stand near Natchitoches, LA. Site index is the height at age 25 years. A = up-slope, B = midslope, and C = down-slope blocks.

The soil bulk density in the up-slope and midslope blocks was similar, and the soil in the down-slope block was significantly lighter (table 3). The differences in soil bulk density among slope positions may be the result of different combinations of soil minerals, organic matter, and pore space. These differences produce variations in the availability of water, nutrients, and oxygen in the soils. Goncalves and others (1997) reported that lower bulk density was associated with greater stem volume in 4-year-old *Eucalyptus camaldulensis* in the savanna region of central Brazil. At the Louisiana site, the highest aboveground biomass was associated with the lowest bulk density in downslope; however, the higher biomass was due to higher tree density, not higher site index.

Differences in soil C content could not be distinguished between the slope positions (table 3), suggesting that organic matter content in the soils was similar throughout the study area. Total N and extractable P and K showed only slight differences between the blocks. Soil Ca and Mg, however, showed substantially higher levels in the down-slope block compared to the other two blocks. None of these nutrient contents were associated with site index. Some investigators have noticed that high Mg in the upper layer of soil may negatively impact tree growth (Personal communication. Richard F. Fisher. 2003. Operation Leader, Applied Research & Development, Temple-Inland Forest Products Coorperation, Diboll, TX 75941). It is uncertain, however, if the Mg level in the down-slope block had any such effect in this site. Mori and Kagawa (2000), from their culture experiments, found a negative effect on algal growth if the Ca-Mg ratio in culture media is less than 4. Another study revealed that a decrease in the Ca-Mg ratio was associated with the decrease of soil pH (Barton and Wallenstein 1997). This phenomenon seems to be true in our study site (table 3). However, there is not enough information for us to speculate if a Ca-Mg ratio of 2.0 observed in the down-slope block reduced site quality compared to the up-slope and midslope blocks where Ca-Mg ratios were 3.6 and 3.8, respectively.

The pattern in the mineralizable N with respect to slope position has a much different pattern from the other soil nutrient contents. Mineralizable N systematically decreased from up-slope to down-slope blocks (Table 3) and corresponded with the site index of each slope position. Regression analysis indicated that mineralizable N was significantly and positively correlated with site index ($R^2 = 0.24$, $p < 0.017$, $n = 23$) (fig. 2). This relationship suggested that available N might be a better measurement of the site quality. Other soil nutrients, although important, may not translate directly to site quality.

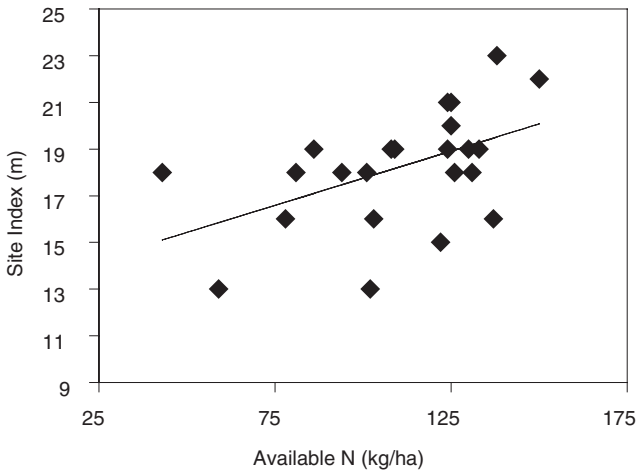

Figure 2—Scatter plot and regression line showing the relationship between site index and mineralizable N in a loblolly pine stand near Natchitoches, LA. The regression model is Y = 13.06+0.046 X where Y = site index and X = mineral N ($R^2 = 0.24$, $p < 0.017$, $n = 23$).

Table 3—Soil bulk density (g per cm³), soil pH, soil carbon (C) and other soil nutrient contents by slope position in a loblolly pine stand near Natchitoches, LA

Slope position	Up-slope	Mid-slope	Down-slope
Bulk Density (*g per cm³*)			
0-5 cm	1.03a[a]	1.09a	0.84b
10-15 cm	1.47a	1.47a	1.36b
20-25 cm	1.52a	1.60a	1.39b
Soil pH at 0-30 cm	5.5	5.2	5.0
Soil C (*Mg/ha*)[b]	21.2	18.7	23.5
N (*kg/ha*)	1,037.4	794.7	994.4
P (*kg/ha*)	10.2	9.9	9.7
K (*kg/ha*)	115.6	84.3	151.1
Ca (*kg/ha*)	876.4	796.6	1,425.0
Mg (*kg/ha*)	243.9	211.4	696.6
Mineral N at 0-30 cm (*kg per ha)*	104.5a	95.7a	65.9b

[a] Within each row, same letters indicate no significant difference among slope positions at $\alpha = 0.10$ level.

[b] These values were calculated based on average nutrient concentration and average soil bulk density of each slope position at the depth of 0-30 cm from soil surface. Therefore, no statistical comparisons were made.

CONCLUSIONS

Delineation between site index and aboveground biomass production was difficult because of different stand densities. Since soil nutrient contents did not correspond to the site indexes of different topographical positions, we conclude that soil nutrient contents alone are not sufficient to account for site quality and productivity. In contrast, the significant and positive relationship between the mineralizable N and site index suggests that available N may be a better measurement of site quality and, perhaps, productivity in this soil.

ACKNOWLEDGMENTS

A Challenge-Cost Share Grant through the USDA Forest Service, Southern Research Station, provided principal funding of this project. Roy O. Martin Timber Company, Temple-Inland Forest Products Corporation, International Paper Company, Weyerhaeuser Company, the School of Forestry, Louisiana Tech University, and the School of Renewable Natural Resources, LSU AgCenter have provided monetary and in-kind support. We thank Bill Wieger, Sam Soule, Brent Dean, Chris Dicus, and Denis Tucker for their help in collecting field data and laboratory analyses.

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FOREST SOIL PRODUCTIVITY ON THE SOUTHERN LONG-TERM SOIL PRODUCTIVITY SITES AT AGE 5

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Abstract—Forest management operations have the potential to reduce soil productivity through organic matter and nutrient removal and soil compaction. We measured pine volume, bulk density, and soil and foliar nitrogen and phosphorus at age 5 on the 13 southern Long-Term Soil Productivity study sites. The treatments were organic matter removal [bole only (BO), whole tree (WT), whole tree and forest floor (WTFF)], and soil compaction (none, moderate, severe). The WT and WTFF treatments reduced pine volume by 18 percent overall compared to the BO plots, with the greatest reductions occurring on the sites with the lowest inherent site quality. Soil compaction had little effect on pine volume, but bulk density of the compacted plots at age 5 was still elevated, by an average of 5 percent, over the noncompacted plots.

INTRODUCTION

The U.S. Department of Agriculture (USDA) Forest Service (National Forest Management Act of 1976) and forest industry in the United States (American Forest and Paper Association 1995) are committed to practicing sustainable forest management. We must understand how forest management operations affect the ability of a site to provide water and nutrients to the growing forest to ensure that forest management is sustainable. If forest management operations reduce available water or nutrients, then the resulting site productivity potential will be decreased. Whereas forest industry often seeks to improve site productivity through more intensive soil manipulation and fertilization, the USDA Forest Service manages its land within the natural limits of site productivity (Powers and others 1996). This management approach requires an even more rigorous understanding of the basic processes controlling site productivity and the mechanisms by which management affects these processes.

Powers and others (1990) reviewed the literature on productivity change and concluded that if forest management were to have negative impacts on future productivity, it would likely do so through the removal of site organic matter or through soil compaction. Using these concepts, the Forest Service initiated a nationwide study on the impacts of organic matter removal and soil compaction on long-term soil productivity (LTSP).

Direct organic matter removals occur due to harvesting, site preparation, and litter harvesting and affect many soil functions that control productivity. Any level of harvesting will remove large quantities of essential plant nutrients from a site. More intensive practices that harvest branches, foliage, and forest-floor organic debris remove a disproportionately large amount of nutrients for the added biomass removed (Johnson and others 1982). Many nutrients, such as phosphorus (P), do not cycle into a given ecosystem from other systems at a rapid rate, so the total nutrient pool cannot recover following harvest removal without amendments (Mann and others 1988). In addition to maintaining nutrient levels, organic matter serves many other important functions in soils. It serves as a substrate for microbial communities, it helps in forming soil structure, and it helps regulate soil water processes.

Soil compaction resulting from machine traffic during harvest and site preparation can increase soil strength and/or decrease aeration porosity. Both processes can reduce root growth, water and air movement, and solute diffusion. Reduced infiltration caused by soil compaction also greatly increases runoff and concomitant erosion.

Loblolly pine (*Pinus taeda* L.) is the most important commercial tree species in the South and is present across much of the region. Therefore, the LTSP study was installed on 13 loblolly pine sites from Texas to North Carolina to test the effects of organic matter removal and compaction across a wide climatic and productivity gradient. The objectives of this paper are to determine (1) loblolly pine productivity, (2) total soil nitrogen (N) and available P, (3) foliar N and P concentrations, and (4) soil bulk density. These tests occurred at age 5 on replicated plots covering a range of organic matter removal and soil compaction levels.

MATERIALS AND METHODS

Study Sites

Thirteen sites were installed across the Southern United States from 1990 to 1998 (table 1). Four sites (statistical blocks) were installed in the Kisatchie National Forest in Louisiana, while three sites each were installed in the DeSoto National Forest in Mississippi, the Davy Crockett National Forest in Texas, and the Croatan National Forest in North Carolina. The soils associated with these installations cover a wide range of soil types and evapotranspiration levels commonly found across the Gulf and Atlantic Coastal Plains.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Table 1—General site description data for 13 locations of the long-term soil productivity study in the southern region

Location	Louisiana	Mississippi	North Carolina	Texas
National forest	Kisatchie	DeSoto	Croatan	Davy Crockett
Soil series each block	Malbis Glenmora Metcalf Mayhew	Freest Freest Freest	Lynchburg Goldsboro Goldsboro	Kurth Kurth Kurth
Precipitation (cm)	145(LA1) 148(LA2-4)	151	136	105
Mean annual temperature (°C)	19	18	16	23
Year established	1990 1992 1993 1993	1993 1993 1993	1991 1991 1991	1997 1997 1997
Previous species	Loblolly	Slash	Loblolly	Loblolly, shortleaf, longleaf

Malbis = fine-loamy, siliceous, subactive, thermic Plinthic Paleudults; Glenmora = fine-silty, siliceous, active, thermic Glossaquic Paleudalfs; Metcalf = fine-silty, siliceous, semiactive, thermic Aquic Glossudalfs; Mayhew = fine-silty, smectitic, thermic Chromic Dystraquerts; Freest = fine-loamy, siliceous, active, thermic Aquic Paleudalfs; Lynchburg = fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults; Goldsboro = fine-loamy, siliceous, subactive, thermic Aquic Paleudults; Kurth = coarse-loamy, siliceous, semiactive, thermic Oxyaquic Glossudalfs.

Treatments

On each site (block), nine treatments were imposed in a 2- by 3-factorial design following a clearcut harvest of the existing stand, with organic matter removal and compaction as the main treatment factors. The three organic matter removal treatments were bole-only harvest (BO), whole-tree harvest (WT), and whole-tree harvest plus forest floor removal (WTFF). Compaction was induced by pulling a weighted multitire road compactor across the sites. Severe compaction was intended to raise bulk density to 80 percent of the root-limiting level (Daddow and Warrington 1983). Moderate compaction was intended to result in bulk density values midway between ambient and severe compaction. After treatment installation, loblolly pine seedlings were planted at 2- by 2-m spacing. Each treatment plot was split into two 0.2-ha plots. One of the split plots was kept clear from competing vegetation when needed by manual removal and directed-spray applications of glyphosate. Competing vegetation was allowed to grow freely on the other split plot. Volunteer pines were controlled manually on all plots except in North Carolina, where they were only controlled on the competition-free split plots. Measurement plots were the interior 0.1 ha of each split plot.

Measurements

At age 5, we measured pine tree height and diameter at breast height in the 0.1-ha measurement plot with height poles and calipers. Pine volume was calculated using equations from Baldwin and Feduccia (1987). Soil samples were collected with a custom core extractor from random locations throughout each measurement plot. The sampler extracted a 5-cm-diameter by 30-cm-length soil core, which was then separated into 0- to 10-cm, 10- to 20-cm, and 20- to 30-cm sections. Ten cores were collected per split plot in Louisiana, Mississippi, and Texas, while three cores were collected per split plot in North Carolina. The soils were dried at 105 °C to a constant weight, and bulk density was recorded. A subsample was collected from each core, prior to drying, for soil nutrient analysis. Soil N was determined by combustion analysis with a C/N/S analyzer. Available soil P was determined by Mehlich III extraction (Mehlich 1984). Foliage was collected in September or October at each site. Foliar N was determined with a C/N/S analyzer, while foliar P was determined by digestion followed by colorimetric analysis.

Data Analysis

The data were analyzed in two ways. First, each State was considered as a separate study and analyzed as a randomized complete-block design. The main treatment effects were determined with Proc GLM (SAS Institute 2000) and separated using Duncan's Multiple Range Test at $\alpha = 0.1$. A lower alpha was chosen in order to increase the power of the test and avoid type II errors. Interaction effects were included in the design but are not discussed in this report, nor are the split-plot effects. To widen the overall scope of inference, the study was also analyzed as a RCBD with all 13 blocks. Main effects and separations were performed as in the analysis by State.

To determine the relative influence of site quality, defined as the average volume across all treatment plots, on pine response to organic matter removal, we plotted the pine volume of the two most severe organic matter removal treatments (WT and WTFF) relative to the least severe organic matter removal treatment (BO) against the mean pine volume for each site.

RESULTS

Loblolly pine volume at age 5 declined with increasing intensity of organic matter removal, but was unaffected by soil compaction. The organic matter removal treatments had no effect on pine volume in Louisiana, which averaged 11.6 m^3 ha^{-1} at age 5 (table 2). In Mississippi, pine volume was reduced from 8.71 m^3 ha^{-1} on the BO plots by an average of 45 percent by WT and WTFF harvesting. In North Carolina, pine volume was 15 percent greater on the WT-harvested plots than on the BO-harvested plots. The WTFF harvesting, however, resulted in an 18-percent decrease in pine volume compared to BO harvesting. In Texas, WT harvesting (5.13 m^3 ha^{-1}) reduced volume by 25 percent, but WTFF-harvested plots (2.42 m^3 ha^{-1}) had only a third the volume of the BO-harvested plots (6.88 m^3 ha^{-1}). Across the 13 sites, pine volume was decreased by about 18 percent by harvesting more organic matter than just the merchantable boles. Within Louisiana, North Carolina, and Texas, compaction had no effect on pine volume. In Mississippi, pine volume increased from an average of 5.44 m^3 ha^{-1} on the noncompacted and moderately compacted plots to 7.38 m^3 ha^{-1} on the severely compacted plots.

The relative impact that harvest intensity had on pine volume was strongly related to overall site quality as defined by average stand volume (fig. 1). Because all stands were the same age and began with the same initial stocking, stand volume is an accurate assessment of site quality. When all comparisons were made (WT vs. BO and WTFF vs. BO), the linear relationship was significant ($P < 0.0001$) and explained a majority of the variation ($R^2 = 0.57$). When the most intensive treatment (WTFF) alone was compared to BO harvesting, the relationship explained even more variation ($R^2 = 0.66$). Because the 13 sites sampled cover a wide spectrum of loblolly pine site types, this finding has important implications. It shows that the inherent productivity of a soil largely determines its susceptibility to harvesting-induced losses of productivity. High-quality sites, such as in North Carolina and Louisiana, were not affected by WTFF removal, but poor-quality sites, such as Texas and Mississippi, were.

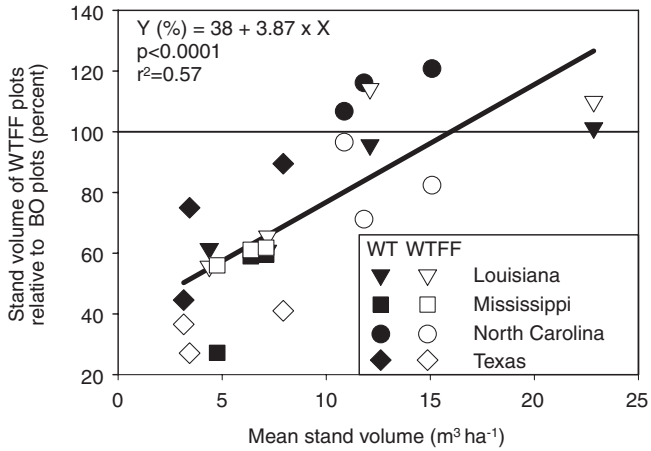

Figure 1—Relative influence of organic matter removal on sites of inherently different quality.

We could not quantitatively compare the average volume estimate of site quality to site index (SI) because the previous stands were not all loblolly pine. However, a cursory examination indicates that SI did not sufficiently indicate which sites were potentially at risk. For example, Texas block 1, one of the poorest sites in terms of average volume, had a SI_{50} for loblolly pine of 26 m. On the other hand, Louisiana block 3, which had a SI_{50} for loblolly pine of 24 m, was one of the most productive sites.

Total soil N and available P were decreased by intensive harvesting in Louisiana and Texas, but not in Mississippi or North Carolina (table 3). In Louisiana, harvesting more than boles only reduced soil N and P by 12 and 23 percent, respectively. In Texas, soil N was reduced 19 percent by WTFF harvesting compared to BO harvesting. In Louisiana and Texas, available soil P was, on average, reduced 22 percent by both increased-intensity harvesting treatments compared to the BO treatment. Over the 13 sites, neither soil N nor P was impacted by harvesting treatments.

Foliar N responded to the organic matter removal treatments much differently than soil N did (table 4). Over the

Table 2—Loblolly pine volume response at age 5 to three levels each of organic matter removal and soil compaction

	Organic matter removal			Compaction			
Location	BO	WT	WTFF	None	Moderate	Severe	Mean
	- -			*m^3 ha^{-1}*			- -
Louisiana	12.33a	10.76a	11.80a	10.59a	12.68a	11.61a	11.63
Mississippi	8.71a	4.33b	5.22b	5.02b	5.85b	7.38a	6.09
North Carolina	12.67b	14.61a	10.49c	12.16a	12.71a	12.90a	12.59
Texas	6.88a	5.13b	2.42c	4.78a	5.13a	5.09a	5.00
Overall	10.32a	8.87b	8.11b	8.42a	9.37a	9.54a	9.11

BO = bole-only harvest; WT = whole-tree harvest; WTFF = whole-tree harvest plus forest floor removal.

Table 3—Soil nitrogen and phosphorus response at age 5 to three levels of organic matter removal

Location	Total nitrogen			Available phosphorus		
	BO	WT	WTFF	BO	WT	WTFF
	- - - - - - *g kg^{-1}* - - - - - -			- - - - - *mg kg^{-1}* - - - - -		
Louisiana	0.57a	0.49b	0.51b	1.60a	1.07b	1.40b
Mississippi	0.55a	0.53a	0.54a	1.36a	1.25a	1.33a
North Carolina	0.72a	0.72a	0.80a	9.09a	8.26a	7.68a
Texas	0.47a	0.40ab	0.38b	1.55a	1.29b	1.14b
Overall	0.58a	0.53a	0.56a	3.26a	2.82a	2.86a

BO = bole-only harvest; WT = whole-tree harvest; WTFF = whole-tree harvest plus forest floor removal.

Table 4—Loblolly pine foliar nitrogen and phosphorus response at age 5 to three levels of organic matter removal

Location	Nitrogen			Phosphorus		
	BO	WT	WTFF	BO	WT	WTFF
	- - - - - - - - - - - - - - - *g kg^{-1}* - - - - - - - - - - - - - - -					
Louisiana	11.4ab	11.5a	11.0b	0.77a	0.74a	0.76a
Mississippi	13.9b	15.1a	13.3b	0.73a	0.72ab	0.71b
North Carolina	9.1b	10.4a	9.1b	0.71a	0.70a	0.67a
Texas	14.8a	15.1a	15.3a	0.95a	0.98a	0.94a
Overall	12.2b	12.9a	11.9b	0.79a	0.78a	0.76b

BO = bole-only harvest; WT = whole-tree harvest; WTFF = whole-tree harvest plus forest floor removal.

13 sites, foliar N concentrations were greatest in plots that had WT harvesting (12.9 g kg^{-1}) compared to BO- and WTFF-harvested plots, which averaged 12.1 g kg^{-1}. In Mississippi and North Carolina, which had the second-highest (14.1 g kg^{-1}) and lowest (9.54 g kg^{-1}) average foliar N concentrations, respectively, the WT-harvested plots had about 11 percent greater foliar N concentrations than the BO and WTFF-harvested plots. In Texas, which had the highest concentrations but the least pine volume, harvest intensity did not affect foliar N. Foliar P concentrations were affected only in Mississippi, where WTFF harvesting reduced foliar P concentrations from 0.73 to 0.71 g kg^{-1}. Although no other significant responses were seen on a State basis, the WTFF treatment reduced the average foliar P concentration from 0.79 g kg^{-1} in BO-harvested plots to 0.76 g kg^{-1}.

Soil compaction was greatly reduced from the first year after treatment to age 5 (table 5). At age 1, the compaction treatments increased bulk density about 12 percent over the noncompacted plots. The lowest increase was 7 percent in Louisiana, while the highest was 22 percent in North Carolina. After 5 years, the average bulk density of the compacted plots was only 4.4 percent greater than the noncompacted plots. Across all sites, the average bulk density of the noncompacted plots was 1.26 Mg m^{-3} at ages 1 and 5. The compacted plots, however, had an average bulk density of 1.41 Mg m^{-3} at age 1, but only 1.31 Mg m^{-3} at age 5, a 7-percent reduction. In North Carolina, which incurred the greatest initial compaction, no effect was detected at age 5. Bulk densities recovered only 2 percent overall in Texas between ages 1 and 5.

DISCUSSION

The results of this study suggest three important findings. First, the removal of organic matter in the form of needles, branches, and litter can be detrimental to early site productivity. Second, treatment responses are site specific. Finally, the data show that elucidating causal mechanisms for productivity change will not be achieved through measurement of static soil properties.

The reduction in early growth caused by organic matter removal is likely due to a reduction in available nutrients. Across Louisiana, Mississippi, and Texas, WT harvesting removed only about 15 percent more biomass than the BO treatment (data not shown). WT harvesting removed about 60 and 78 percent more N and P, respectively, in the biomass removed compared to the BO-harvesting. WTFF harvesting removed about 54 percent more biomass than the BO treatment and about 196 and 240 percent more N and P, respectively. In the western gulf coast sites (Louisiana, Mississippi, and Texas), soil P was inherently low, averaging only 1.5 mg kg^{-1} in the BO-harvested plots. The critical level for loblolly pine is 3 mg kg^{-1} (Wells and others 1973), making these soils quite P deficient. Accelerated removals

Table 5—Soil bulk density (0-10cm) immediately after the application of three levels of soil compaction at age 1 and again at age 5

Location	Age 1			Age 5		
	None	Moderate	Severe	None	Moderate	Severe
	- - - - - - - - - - - - - - - - - - - *Mg m^{-3}* - - - - - - - - - - - - - - - - - - -					
Louisiana	1.32b	1.41a	1.43a	1.28b	1.31a	1.32a
Mississippi	1.31b	1.41a	1.42a	1.30b	1.37a	1.35a
North Carolina	1.20b	1.47a	1.45a	1.17a	1.22a	1.28a
Texas	1.18b	1.33a	1.32a	1.23c	1.32a	1.28b
Overall	1.27b	1.41a	1.41a	1.25b	1.30a	1.31a

of P through more intensive biomass harvesting probably exacerbated this deficiency, even though available soil P was not affected in Mississippi. The lack of correlation between soil P change and productivity change at Mississippi is not surprising; the method used to estimate available P was not designed to detect such low concentrations of P, and Mississippi had the lowest available P of any of the sites.

If the observed reduction in productivity was due to a reduction in available P, then long-term findings will likely reflect these early results. Phosphorus becomes available through weathering of parent materials and dissolution from fixed States (McBride 1994) and from atmospheric deposition. Jorgensen and Wells (1986) suggest that on highly weathered soils, deposition provides the only significant input of P. In much of the Coastal Plain, these reactions and deposition inputs occur much more slowly than the expected forest rotations. Since P fertilizer is retained in the mineral soil (Pritchett and Comerford 1982), applications of P fertilizer can easily remedy these P deficiencies. While P fertilization is common on deficient forest industry lands, it is not common on national forest lands in the South.

Harvesting also removed substantial quantities of N, which is limiting throughout much of the South. However, the effect of harvest intensity on soil N availability is more complex than for P. While increased removal of organic matter removes a portion of the total site N, forest management operations may increase N availability in the first few years after harvest. Burger and Pritchett (1984) showed that disturbances that increased temperature, water content, and juxtaposition of soil and organic matter increased N availability, even though total N was reduced. Slash and forest floor insulate soils after harvest, and removing them may have increased soil temperature. Removing the slash and forest floor also may have removed a sink for N immobilization, thereby increasing short-term N availability. Theoretically, if atmospheric deposition and biological fixation does not replace the N removed in harvest, then long-term soil N availability will be reduced.

Foliar analysis indicated that P was much more limiting than N on all sites except in North Carolina. Established critical levels for foliar N and P are 12 and 1 g kg^{-1}, respectively (Wells and Allen 1985). Foliar N in Mississippi and Texas consistently exceeded 12 g kg^{-1} regardless of treatment and was nearly 12 in Louisiana. Only the foliar N in the North Carolina plots indicated a N deficiency. Foliar P, however, was only about 0.7 g kg^{-1} in Louisiana, Mississippi, and North Carolina, and about 0.96 g kg^{-1} in Texas. These results indicate that although N availability may have been limiting for short periods of time, P was the more limiting nutrient.

Soil compaction had much more variable effects on productivity. In Louisiana, North Carolina, and Texas, compaction had no statistically verifiable effect on pine volume production. However, compaction had substantial impacts, both positive and negative, on a block basis. Compaction (average of two compaction treatments) reduced volume production compared to no compaction on four blocks (LA1, LA3, NC3, TX3), but only LA3 and TX3 had reductions > 10 percent. Conversely, LA2, LA4, MS2, MS3, and NC1 had > 10 percent improvement on the compacted plots than on the noncompacted plots. The responses at age 5 to compaction may be due to several factors. First, the Louisiana and Mississippi soils had been compacted previously by unregulated grazing. Second, early root growth may have occurred in root channels and other remnant soil voids (Parker and Van Lear 1996). Finally, as the data indicate (table 5), the compaction has largely been alleviated by age 5 through natural processes such as shrinking and swelling, frost heaving, and biological activity. If root growth in old root channels or other remnant soil voids occurred, then compaction may have a greater effect as the stand ages and remnant root channels are filled and new roots must explore the compacted soil matrix. These results are in direct contrast to several studies that have found significant and substantial reductions in productivity on skid trails and log landings (Aust and others 1998, Hatchell 1981), and raise the question of how similar the experimentally applied compaction of the LTSP study is to traffic-induced compaction. One possibility is that the growth reduction found in previous studies was due to the loss of organic matter rather than compaction. Another factor was that compaction may have reduced competing vegetation, thereby allowing site resources to be allocated to pine trees, which improved growth over the noncompacted plots. Further analysis of the data will help to understand this interaction.

CONCLUSIONS

At age 5, loblolly pine volume production was reduced 18 percent by harvesting practices that removed more than just the merchantable bole. Using the USDA Forest Service guideline for evaluating productivity, which states that 15 percent losses in productivity are nonsustainable (U.S. Department of Agriculture, Forest Service 1987), the whole-tree or total organic matter removal treatments in this study are not sustainable practices. The reductions in productivity were closely related to inherent site productivity: Sites with low inherent productivity were much more sensitive to treatments than highly productive sites. The analysis of soil and foliar nutrients indicate that the loss of productivity was likely due to the removal of P on inherently P-deficient soils. These practices, therefore, are unsustainable without amelioration. This study also indicates that, through age 5, soil compaction does not negatively impact forest productivity on these soils and may be beneficial to pine productivity in some cases. Negative compaction impacts may appear as the stands age, however, and may be more prevalent on other soil types.

ACKNOWLEDGMENTS

The authors gratefully acknowledge Morris Smith, Paul Jackson, Tom Christensen, Bob Eaton, and others for installation and maintenance of the Long-Term Soil Productivity study sites. We thank Mary Anne Sword, Tom Dean, and Minyi Zhou for reviewing an earlier draft of the manuscript.

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DEFINING STREAMSIDE MANAGEMENT ZONES OR RIPARIAN BUFFERS

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Abstract—Forestry Best Management Practices (BMPs) have been highly successful in protecting water quality throughout the Southeast. Numerous studies have found them to be effective in protecting water quality. Despite being mostly voluntary, compliance is generally about 90 percent across the region. Streamside Management Zones (SMZs) or riparian buffers are specified for perennial streams in all of the southeastern BMP manuals, and buffer width generally increases with land slope. However, that is where the similarity ends. Each State has specified different buffer widths in a variety of methods. For example, a creek with a side slope of 40 percent requires a 120-foot buffer in South Carolina but the same stream would require a 50-foot-wide buffer in Mississippi. We compared the various State specifications of SMZ on stream networks from watersheds in northwestern South Carolina, including three on the Clemson Experimental Forest where we evaluated South Carolina's BMPs. We also tested methodologies on an independent watershed in north Georgia. We found guideline differences consistent between watersheds and watershed differences consistent between guidelines. Size of SMZ was more influenced by drainage density than side slope, despite the explicit use of side slope in the guidelines. There was no entirely satisfactory way to map SMZ areas with publicly available data.

INTRODUCTION

Voluntary Forestry Best Management Practices (BMPs) have been successful in protecting water quality throughout the Southeast (Shepard 2002). A variety of studies during the 1960s to 1980s evaluated water-quality impacts of forestry practices (Beasley 1979, Dickerson 1975, Douglass and Goodwin 1980, Hewlett 1979, Hewlett and Douglass 1968, Neary and others 1986, Riekerk 1983, Ursic 1975). They found several practices that contributed to sedimentation, the most common impairment to water quality caused by forestry (Yoho 1980). Forestry BMPs were then devised to eliminate those practices. A number of later studies found BMPs effective in preventing water-quality degradation noted in the earlier studies (Florida Department Of Environmental Protection 1997, Frazee 1996, Williams and others 1999). Therefore, throughout the forestry community of scientists, industry, loggers, and landowners, BMPs are seen as sufficient to protect water quality. Monitoring programs have shown that there is a high degree of compliance with these voluntary programs.

Voluntary BMP compliance results in substantial cost savings to the public. Kilgore and others (2002) estimated that compliance monitoring in the Eastern United States cost an average of $60,000 per year in States with voluntary programs, compared to $500,000 to $700,000 per year for States with regulatory programs. Western States spend even more on regulatory programs, averaging over $1 million per year. BMPs do have a considerable private cost to forest landowners. Cubbage and others (2002) reviewed costs of BMP compliance and showed Streamside Management Zones (SMZ) had small direct costs (< 10 percent of total BMP cost) but high opportunity costs. On U.S. Forest Service land, the lost opportunity for management of SMZ land was estimated as 26 percent of sale revenue. They also reported an estimated SMZ opportunity cost of $2,530 per acre in Arkansas. All States have an SMZ recommendation, which varies in width by land slope (table 1). Opportunity costs of compliance with recommended SMZ width will vary considerably. In order to plan management activity, it would be very useful to have an accurate planning map of SMZ width.

During the last 3 years, we have developed an ARC/INFO AML program to map variable width SMZ areas (Lipscomb and Williams 2000, 2002; Williams and others 2003). This

Table 1—Widths (feet) of SMZ recommended in several Southeastern United States forestry BMP manuals[a]

Slope percent	0	10	20	30	40	50	60
VA[b] (warm)	50	50	50	50	50	50	50
VA[b] (cold)	65	65	70	100	100	125	125
VA[b] (DW)	100	150	150	150	200	200	200
NC[c] (warm)	50	50	50	50	50	50	50
NC[c] (cold)	50	65	70	100	100	125	125
SC[d] (warm)	40	80	80	120	120	160	160
SC[d] (cold)	40	120	120	160	160	200	200
GA[e]	40	40	40	70	70	100	100
TN[f]	25	45	65	85	105	125	145
KY[g]	25	45	65	85	105	125	145
MS[h]	30	40	40	50	50	60	60

SMZ = streamside management zones; BMP = best management practices; warm = warm water fishery; cold = cold water fishery; DW = drinking water supply.

[a] Width for the outer edge of the zone of minimal soil disturbance on one side of the stream.

[b] Virginia Department of Forestry (1997).

[c] North Carolina Division of Forest Resources (1989).

[d] South Carolina Forestry Commission (1994).

[e] Georgia Forestry Commission (1999).

[f] Tennessee Division of Forestry (1993).

[g] Springer and Perkins (1997).

[h] Mississippi Forestry Commission (2000).

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

program maps the SMZ width on each side of the stream, dependent on the slope, as defined in the BMP manuals. We have used the program to evaluate differences in SMZ width on a series of watersheds in the Piedmont of South Carolina and Georgia. Here we will present the differences found and examine limitations in mapping SMZ widths.

METHODS AND RESULTS

Phase 1. Comparison of State Guidelines

Methods—The first section of the study was to evaluate differences in Southeastern State guidelines. For this phase, we utilized five watersheds in western South Carolina. Four of the watersheds were small experimental watersheds on the Clemson Experimental Forest (34°44'50"W 82°52'27"N) used in a prior study testing the South Carolina Forestry BMPs. Williams and others (1999) described the soils, vegetation, and treatments on these watersheds. In general, they are small watersheds (97 to 165 acres) with steep slopes (table 2). For each watershed, streams were mapped from 1:12,000 photographs and field checked; contour lines were digitized from 1:24,000 quadrangle maps and converted to a Digital Elevation Model (DEM) with a cell size of 40 by 40 feet. The fifth watershed, Three and Twenty Creek, located southeast of Clemson, SC (34°35'59"N 82°44'19"W) was considerably larger (59,000 acres) and was designated by the U.S. Geological Service (USGS) Hydrologic Unit Code 03060101-100. On this watershed, streams were hand digitized from USGS quadrangle maps to include all blue lines (either solid or dotted). A DEM with 40- by 40-foot grid cells was developed for this watershed in the same manner as for the four smaller watersheds.

Each of the five watersheds was then analyzed with the ARC/INFO AML program to map SMZ widths (Lipscomb and Williams 2002). The program utilizes the DEM to calculate the right and left side slope on 40' sections of the stream. These slopes are then put into slope classes as defined in the various BMP manuals; that is, the slope classes in table 1 are used to define an SMZ width for that section and side of the stream. These are combined for all sections of the stream, and an SMZ area is mapped. The SMZ area was determined for guidelines from Georgia, Kentucky, Mississippi, North Carolina, and South Carolina. Tennessee and Virginia were mapped but are not presented since they are the same as Kentucky and North Carolina, respectively. SMZ area was then standardized as percentage of total watershed area.

Table 2—Distribution of land slopes in the four study watersheds used for BMP evaluation

Slope categories	0–5	5–20	20–40	> 40
	- - - - - - - - - *percent* - - - - - - - -			
Watershed				
Kenamore One	9.4	17.1	55.1	18.4
Kenamore Two	10.2	9.7	47.7	32.4
Ramsey Bridge	16.8	12.4	53.8	17.0
Holly Springs	12.3	26.7	46.5	9.3

BMP = best management practices.
All slopes were calculated from contours extracted from USGS quadrangle maps.

Results—Application of each State SMZ guidelines to the same watersheds reveals a number of variations. The ways each State deals with slope differs (table 1). Although Mississippi generally requires the least in streamside management zone and South Carolina the most, the relative ranking changes with slope. Kentucky and Tennessee have small requirements at slight slopes but the requirement increases steadily. Kentucky has a different width for every 5-percent change in slope, Tennessee has a different width for every 10-percent change in slope, whereas South Carolina and Mississippi use 0 to 5 percent, 5 to 20 percent, 20 to 40 percent, and over 40-percent groupings. Georgia is slightly different, and North Carolina and Virginia only have slope differences in their cold water fishery guidelines. All the States agree SMZ width should increase with slope, but each State has a different interpretation as to the best way to group slope classes.

Differences in the State guidelines interact with the topography of individual watersheds (table 3). In general, differences in State guidelines are consistent between watersheds, with South Carolina always specifying the greatest area and Mississippi the least. Also the percentage of watershed in SMZ increases with the percentage of steep slopes on the watershed. Kenamore Two, with over 80 percent of the watershed at slopes greater than 20 percent, has the greatest percentage of watershed in SMZ, regardless of which State guidelines are used. Kentucky shows the widest variation between watersheds with SMZ, representing 10.5 percent of Holly Springs and 20.0 percent of Kenamore Two.

However, the differences in SMZ area are not primarily due to differences in side slope. Table 4 standardizes SMZ width by stream length rather than watershed area. In this case an overall average SMZ width characterizes the watersheds and BMP differences. The North Carolina values demonstrate rounding errors and variations in the program because the NC guidelines specify a uniform 50-foot width. When standardized by the length of stream there is no difference between the watersheds for most of the different State BMP guidelines. Kentucky is an exception because it has much narrower slope categories than the other States. The required SMZ changes for every 10-percent change in slope in the Kentucky guidelines, whereas the required SMZ width is the same over 20 percent or more classes in the other States. The total area in SMZ is more heavily influenced by length of stream than by the slope of the watershed.

The Three and Twenty watershed was added as a test of the technique on a larger watershed. It is similar to the four forested watersheds but represents the smallest watershed normally mapped by EPA in water-quality assessment, which are watersheds designated by an 11-digit number of the USGS Hydrologic Unit Code. This is the smallest normal level of watershed delineation in publicly available GIS data. The SMZ on Three and Twenty Creek was calculated from GIS data that was publicly available for the stream.

Table 3—Variation in size of Streamside Management Zone (SMZ) calculated from specifications in Southeastern U.S. forestry best management practice guidelines

Watershed data	Kenamore One	Kenamore Two	Ramsey Bridge	Holly Springs	Three and Twenty
Size (*acres*)	104	91	144	167	59,000
Georgia	10.1 (9.7)	16.0 (17.6)	19.0 (13.2)	16.5 (9.7)	1,767 (3.0)
Kentucky	11.3 (10.9)	18.2 (20.0)	20.5 (14.2)	17.6 (10.5)	1,22 (2.1)
Mississippi	9.4 (9.0)	14.9 (15.9)	17.6 (12.2)	15.3 (9.2)	1,380 (2.4)
North Carolina	12.3 (11.8)	19.3 (21.2)	23.5 (16.3)	20.4 (12.1)	2,177 (3.7)
South Carolina	21.9 (21.0)	32.8 (36.0)	40.1 (27.8)	35.0 (20.1)	2,560 (4.3)

SMZ = streamside management zone.
All sizes are in acres and represent the total area contained in both primary and secondary SMZ. Numbers in parentheses are percents of total watershed area.
All data were generated by ARC/INFO AML using distances specified in each State's guidelines.
Data for Virginia is identical to North Carolina, and Tennessee is identical to Kentucky, so these States are not shown. Warm water fishery guidelines were used in each case.

Table 4–Variation in overall average width of Streamside Management Zone calculated following specifications in Southeastern U.S. forestry best management practice guidelines

Watershed	Kenamore One	Kenamore Two	Ramsey Bridge	Holly Springs	Three and Twenty
Stream length (*feet*)	5,343	8,393	9,040	10,250	952,565
Georgia	41.2	41.5	40.4	39.7	40.2
Kentucky	46.0	48.8	43.6	42.4	27.9
Mississippi	38.3	38.7	37.4	36.9	31.5
North Carolina	50.1	50.1	49.9	49.2	49.8
South Carolina	85.3	85.2	85.2	84.3	58.5
Stream density (*feet per acre*)	51.2	92.3	71.0	54.0	16.1

SMZ = streamside management zone.
All widths are for one side of the creek and represent the total width of both primary and SMZ. Data source is same as Table 3. Average width was calculated by dividing total SMZ area by stream length.

There is a large difference in the proportion of Three and Twenty Creek watershed mapped as SMZ compared to the four experimental watersheds (table 3). Some of the difference can be attributed to flatter slopes on the larger watershed as can be seen in the narrower average width for Kentucky and South Carolina in table 4. However, much of the difference is attributable to stream length, represented by the drainage density term in table 4. Drainage density is expressed in feet of stream length per acre of watershed area. It is clear that the publicly available data does not represent as many streams in the larger watershed.

Each of the State BMP manuals has criteria to determine the extent of perennial (and in some cases intermittent) streams where an SMZ is recommended. The streams on the four experimental watersheds were mapped according to the South Carolina Guidelines. The streams of the Three and Twenty watershed were mapped only from the USGS "blue lines". It seems quite clear that these data do not represent length of streams specified by the ground criteria.

PHASE 2. Techniques to Delineate Stream Length Appropriate to State Guidelines

Methods—The second phase of this study sought to examine methods for estimating the area included in SMZ from public data that are more accurate than the present "blue lines". A model watershed was chosen in the Chattahoochee National Forest in northern Georgia. This was a 3,960-acre watershed in the Jacks Gap Quadrangle (34°49'57"N 89°49'00"W). Data collected for this watershed consisted of three publicly available sources. Contours were taken from the Jacks Gap Quadrangle map, as were the "blue line" streams, and from panchromatic Digital Ortho Quarter Quads. All data were then rectified to the same coordinate system (Georgia West State Plane, North American Datum 1927). Contour lines were then used to create a DEM as described in phase one. Two techniques were evaluated to estimate stream lengths: Strahler valley orders and stream generation from DEM.

Two criteria were used to determine the smallest valley to be used with the valley order technique. A valley had to be present on three consecutive contour lines (for Jacks Gap this would represent 60 feet of down valley slope) and be at least 300 feet long. These criteria were generally evaluated at a screen resolution of 1,038 by 764 pixels with a representative fraction of 1:7,200 (1 inch = 600 feet. A line was digitized representing the lowest points on each contour line. All valley bottoms were digitized uphill beginning at a "blue line" stream or a digitized valley bottom. These lines were then cleaned and formed into continuous networks for each stream crossing the quadrangle boundaries. Digitizing was done in the uphill direction because that allowed the analyst to use a right-hand maze rule in order to digitize to all valley bottoms. Each line segment in the network was then flipped in order to make the network point down hill.

Once a network of valley bottoms was created, it was then evaluated by the Strahler (1957) Stream Order rule. This rule makes all unbranched segments first-order valleys. Where two first-order valleys merge, the valley becomes second order; two second orders merge to form a third order, etc. If a lower order stream merges with a higher order, there is no change in order. Valley order was then used to generate a series of stream networks. Each network assumed that a stream needing an SMZ corresponded to a valley of specific order. At the outlet, the valley was a fifth order, allowing evaluation of first through fourth order. An SMZ was then assigned to each stream network using the AML program. The North Carolina warm water SMZ definition was used in all analyses.

Stream networks can be automatically generated from a DEM. There are a series of intermediate steps that create grid data in a given sequence. The first step is to make sure there are no closed depressions, called sinks, in the DEM. A filter of the DEM is run a series of times that fills the closed depressions with the mean value of the grid cells surrounding it called filled sinks. A second grid, called flow direction, determines downhill direction for each grid cell. A third, called flow accumulation, determines the number of uphill grid cells for each cell. From the flow accumulation grid, a stream network can be generated in a simple manner of declaring the minimum watershed size in grid cells. For example, the analyst can specify a minimum watershed size of 1,000 grid cells, and each grid cell with more than 1,000 cells uphill will be formed into a stream network using the direction grid. For 40- by 40-foot grid cells, this would represent an area of 1,600,000 square feet or roughly 40 acres. Exactly 40 acres would be 1,089 grid cells.

We used the 40-foot grid cell DEM created for the Jacks Gap Quadrangle to create grids of filled sinks, flow direction, and flow accumulation. The example watershed boundary was used to extract flow direction and flow accumulation grids containing data for only the example watershed. Stream networks were then created corresponding to 1-, 2-, 5-,10-, 20-, and 40-acre subwatersheds. These stream networks were then used to generate SMZ areas for each subwtatershed size. The North Carolina warm water SMZ definition was used for all SMZ analyses on networks determined by DEM analysis.

Results—The example watershed was chosen to be similar to the four experimental watersheds used in phase one where streams requiring SMZ protection were delineated by ground application of the BMP guidelines. It was 40 times larger than the experimental watersheds but 10 times smaller than watersheds normally evaluated by EPA. Using the above criteria for a minimum valley, the outlet was a sixth-order valley. The lengths of the fifth- and sixth-order streams were quite short, and SMZ area was determined for networks of fourth and higher to first and higher (table 5).

On this watershed, the "blue line" streams were 16.2 miles long and had an SMZ of 192 acres or 4.8 percent of the watershed. The percentage is similar to the 3.7 percent on the Three and Twenty watershed (table 3). The "blue line" values are intermediate between the values for valleys above a fourth order and a third order. The blue lines on the quad sheets appear to have used fourth-order valleys and used the original Horton (1945) definition of order, which assigns the order not to segments but to the longest tributary. In the Strahler system, a fourth-order stream extends only to the junction of the two third-order streams that form it. In the Horton system, the third-order stream extends all the way to the head of the longest tributary. Thus, the blue line "fourth-order" streams are longer than the streams defined by the Strahler method.

Using second order valleys as the limit for a perennial stream most closely approximated the SMZ delineated by field examination. For the North Carolina warm water SMZ definition, SMZ area was from 11.8 to 21.2 percent of the four experimental watersheds in phase one. SMZ area was 13.1 percent of the example watershed using a second-order valley as the minimum size of a valley with a perennial stream.

Using automated mapping of stream networks from the DEM produces similar values to the valley order technique (table 6). In this case, the "blue line" streams are best approximated by a minimum watershed slightly more than 10 acres. Likewise, the SMZ most like those on the field-checked experimental watersheds was found with a two-acre minimum watershed size.

Table 5—Results of Strahler Valley Order Method

	Blue line streams	6th	5th	4th	3rd	2nd	1st
Number of segments	164	12	37	102	159	354	711
Length of segments (miles)	16.2	0.87	2.41	6.37	10.9	23.2	74.4
SMZ (*acres*)	192			114	246	520	1,386
SMZ (*percent of watershed*)	4.84			2.88	6.20	13.1	35.0

SMZ = streamside management zones.
All valleys, more than 60 feet fall and 300 feet long, were ordered, and North Carolina SMZ was determined for networks of valleys fromfirst to fourth order. Number and length of stream segments were determined for each network of lines digitized in valley bottoms. Note the length of segments in this table isthe length of only those of the order listed. SMZ area was determined not only for those segment lengths but for lengths of all higher order valleys.

Table 6—Summary of stream lengths and SMZ areas determined by stream network calculated from DEM

	Blue line Streams	40	20	10	5	2	1
				acres			
Number of segments	164	37	79	142	309	652	1,460
Length of segments (*miles*)	16.2	3.56	10.4	17.6	23.8	46.6	80.3
SMZ (*acres*)	192	168	254	336	458	659	1,007
SMZ (*percent of watershed*)	4.86	4.23	6.41	8.48	11.6	16.6	25.4

SMZ = streamside management zones; DEM = digital elevation model; BMP = best management practices.
Each network was determined by assuming a stream was formed by a minimum watershed size varying from 1 to 40 acres. All SMZ areas are for the North Carolina BMP specifications. Note the length of segments includes all segments to the outlet for each network. SMZ area was calculated based on these segments.

DISCUSSION

SMZ areas may occupy a significant portion of steeper Piedmont watersheds. Management planning would be greatly aided with a reliable method to map SMZ zones without the expense of ground mapping. However, mapping SMZ zones accurately will not be a trivial task. The size of SMZ varies considerably among the Southern States, and the size also increases rapidly in steeper terrain. The most significant factor, however, is not side slope but rather the length of streams or drainage density, which increases rapidly with increasing slope.

Mapping SMZ widths from publicly available GIS data under estimates the size of SMZ that will be determined by field mapping. Streams designated by blue lines on 1:24,000 USGS quadrangle maps are larger than those that meet field definitions of perennial streams. We examined two techniques to map streams from other public data.

Mapping valleys from contours and assigning Strahler order to valley segments produces a stream network that can approximate the field values. Using set criteria for a minimal valley of 300 feet in length and 60 feet in total elevation change allowed us to define a second-order valley as a close approximation of field delineated perennial streams. Such mapping is widely applicable as the relationship of stream length, drainage area, and stream order are well recognized (Horton 1945, Leopold and others 1964). The technique has two limitations: mapping of the valleys is done by hand digitizing and is labor intensive; and Strahler orders are limited to several discreet values (1 to 7 or 8), and stream length and number increase exponentially as order decreases.

Generation of stream networks automatically from DEMs can be done quickly. The limitation on alternatives is only the number of grid cells in the DEM. The length of stream is more closely linear to the minimum area of subwatershed. In the case studied, a 2-acre minimum most closely approximated the field data. However, this technique does not have any geomorphic basis, and the minimum may be specific to each individual watershed. We found that the two-acre minimum was not satisfactory for broad river valley segments. There, the GIS placed a number of parallel pseudo streams across the valley, incorrectly placing the SMZ across the valley bottom.

Neither of the alternative techniques was entirely successful in accurately mapping SMZs for forest management planning. Also these methods do not address the question posed by the differences in State guidelines— What SMZ is both sufficient and necessary to protect water quality?

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Pine Nutrition

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COPPER DEFICIENCY IN PINE PLANTATIONS IN THE GEORGIA COASTAL PLAIN

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Abstract—Copper deficiencies have been observed on several intensively managed pine plantations in the Georgia Coastal Plain. Loblolly pine (*Pinus taeda* L.) and slash pine (*Pinus elliottii* var. *elliottii* Engelm.) displayed plagiotropic growth within a year after planting on very acid, sandy soils. Typically, symptoms show up during the summer after transplanting. The needles on severely affected seedlings are thin and flaccid. After the roots reach greater depths, a branch or stem regains apical dominance, and the seedling usually recovers. Although many trees achieve a normal appearance, some stems remain twisted. Three tests were conducted in Pierce County, GA, to determine if the addition of copper (36 kg per ha of copper sulfate) or dolomitic lime (6.7 metric tons per ha) would ameliorate the problem on a Mascotte soil. The treatments were useful in maintaining the vigor of newly planted pine seedlings. Both the copper and lime treatments affected growth of the newly planted, as well as older, symptomatic seedlings. Both treatments were more efficacious when applied as a prophylactic treatment (before planting) than as a curative treatment (after symptoms develop). The lime treatment increased the population of herbaceous weeds.

INTRODUCTION

Copper is an essential element for normal growth of pines. Copper deficiencies have been reported on slash pine (*Pinus elliottii* var. *elliottii* Engelm.) in Australia (Simpson and Grant 1991), Monterey pine (*Pinus radiata* D. Don) in New Zealand (Hunter and others 1990), and maritime pine (*Pinus pinaster* Aits) in France (Saur 1994). In the Southern United States, many sites are not deficient in copper, and pines typically do not exhibit copper deficiency symptoms. Forest soils in the Lower Coastal Plain typically have from 0.3 to 1.4 ppm copper (NCSFNC 1992). However, most of the copper ions are bound to organic matter, so soil testing may provide a poor indication of levels available to the trees (Landis and Van Steenis 1999).

In the Southeastern United States, copper in pine needles has been correlated with soil acidity—the lower the soil pH, the lower the copper level in the foliage (NCSFNC 1992). Copper is easily desorbed when soil pH is low (McLaren and others 1990). Also, on some sites, soil cultivation could have a lasting effect on soil copper. For example, Schmidtling (1985) reported that plowing and disking effects could reduce soil copper levels to 1.1 ppm (vs. 1.6 ppm for controls). This difference was detected 24 years after the initial cultivations.

About 1990, a copper deficiency was noted on a Pamilco muck soil in Bladen County, NC (personal communication: Gregory Conner). The area had been treated with triple super phosphate prior to planting loblolly pine seedlings. No reports of copper deficiency of pines growing in the Southern United States are known prior to 1990. However, we have received reports of copper deficiencies of pines on intensively prepared Spodosols in Echols, Effingham, and Pierce Counties, GA. The soils are very acid (pH 3.5 to 4.3) and are represented by the Mascotte and Leon soil groups. These soils have a Bh horizon with many sand grains coated with organic matter. Pines have been planted on these soils for decades without obvious signs of copper deficiency.

Symptoms

A loss of the upright growing habit was observed at all three sites (fig. 1). On many seedlings there were twisted branches, and there was a “limpness” of needles. In some cases, needles were stunted (fasical dry weight reduced by 40 percent or more).

Intensive site preparation was conducted prior to the onset of plagiotropic growth. The Effingham County site was disk-harrowed, bedded, and planted with slash pine in November

Figure 1—Loblolly pine seedling showing symptoms of copper deficiency. (Photo taken by Scott Cameron in April 2001.)

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

of 1998. Herbicides (atrazine and sulfometuron) were applied to control herbaceous weeds on part of the area, and there was no fertilization. Symptoms began to appear the following year on areas treated with herbicides and on areas where no herbicides were applied. The Pierce County site was disk-harrowed in April, bedded in June, and double-bedded in August 1997. The area was treated with triclopyr and imazapyr on November 25, 1997, and loblolly pine seedlings were machine planted on March 15, 1998. Herbaceous weeds were treated with hexazinone and sulfometuron in May 1998, and the area was fertilized with 140 kg per ha of diammonium phosphate on June 19, 1998. Symptoms were observed in the summer of 1998.

Foliar Analyses

Typically, copper levels in needles of healthy loblolly pine seedlings in nurseries range between 2 and 10 ppm (Boyer and South 1985). On sites in the Lower Coastal Plain, the mean for young pine stands may be 3 ppm with a range of 1 to 5 ppm (NCSFNC 1992). Analyses of foliage sampled in the fall at the Pierce County site indicated 0 ppm of copper for affected seedlings and 2.8 ppm for unaffected seedlings (Auburn University Soils Lab.). Analyses of older needles collected in the spring at the Effingham County site indicated affected seedlings had 1.3 to 1.9 ppm of copper. Affected needles collected from the Echols county site had 2 to 3 ppm of copper (analysis from a different laboratory). Some believe the timing of foliage sampling is important, and that xylem sap may be a better predictor of copper deficiency than foliar analysis (Saur and others 1995).

METHODS

Three experiments were installed on a Mascotte soil in Pierce County, GA. The studies tested the hypothesis that adding copper or lime does not ameliorate plagiotropic growth. Two preliminary studies (Tests 1 and 2) were installed in 1999 and an operational study (Test 3) was installed in 2000.

Tests 1 and 2: Treatments Applied Before And After Planting

For Test 1, each plot contained two rows of newly planted seedlings (planted on November 5, 1999), and treatments were replicated five times. In Test 2, plots contained one or two rows of seedlings that were planted on January 16, 1999, and were already showing symptoms of copper deficiency. Treatments included: a copper treatment of 36 kg per ha of copper sulfate, a dolomitic lime treatment of 6.7 metric tons per ha, a combination of copper and lime, and untreated controls. Treatments were applied by hand on October 1, 1999, and then the area was bedded. Treatments were replicated five times. Loblolly pine seedlings were planted on November 5, 1999, and herbicides (hexazinone and sulfometuron) were applied in early May. Seedling measurements were recorded on March 27, 2001.

Test 3: Operational Treatments Applied Before Planting

Treatments included: a copper treatment of 36 kg per ha of copper sulfate, a dolomitic lime treatment of 6.7 metric tons per ha, a combination of copper and lime, and untreated controls. Plots contained six rows of seedlings, and treatments were replicated four times in a randomized complete block design. The lime was applied with a skidder and pull wagon on November 16, 2000. The copper was applied to the beds by hand, and the area was bedded for the second time on November 17. The entire area was treated with triclopyr (3.36 kg a.i. per ha) and imazapyr (140 g a.e. per ha) on October 10. Loblolly pine seedlings were planted on December 15, at approximately 2,500 trees per ha. The herbicide sulfometuron (105 g a.i. per ha) was applied in bands on May 22, 2001. The entire area was fertilized with diammonium phosphate (280 kg per ha) on August 30, 2001. Seedling measurements (50 trees per plot) were recorded on December 13, 2002.

RESULTS AND DISCUSSION

Both the copper and the lime treatments affected growth of newly planted and symptomatic seedlings (table 1). Both treatments were more efficacious when applied as a prophylactic treatment (before planting in Tests 1 and 3) than as a curative treatment (Test 2). The lime treatment increased soil calcium, magnesium, phosphorus, and also increased the weed population and soil pH.

Test 1: Treatments Applied Before Planting

Both the copper treatment and the lime treatment increased seedling height and groundline diameter, and reduced plagiotropism. Untreated seedlings were about 67 cm tall

Table 1—Probability of a greater F-value of treatment effects on height, groundline diameter and deficiency symptoms of loblolly pine seedlings

		Test 1			Test 2			Test 3	
Source	df	Height	GLD	DS	Height	GLD	DS	Height	DS
		P > F value							
Block	3 – 4	0.214	0.552	0.078	0.001	0.001	0.001	0.062	0.357
Lime	1	0.001	0.083	0.001	0.740	0.568	0.537	0.013	0.001
Copper	1	0.003	0.056	0.003	0.011	0.059	0.009	0.016	0.002
L x C	1	0.253	0.334	0.001	0.953	0.400	0.920	0.989	0.001
Error	9 – 12								

GLD = groundline diameter; DS = deficiency symptoms; B = block; L = lime; C = copper.

compared with 88 cm tall for copper-treated seedlings. Seedlings treated with both copper and lime were 102 cm tall. The copper treatment increased ground-line diameter by 5 mm (table 2). Tree form was abnormal for 61 percent of the untreated seedlings whereas lime or copper seedlings were 9 to 18 percent abnormal (table 3). Needle symptoms were evident on 75 percent of the untreated seedlings but only 15 to 18 percent of the seedlings growing in copper- or lime-treated plots had needle symptoms.

Test 2: Treatments Applied After Symptoms Appear

Copper and lime were applied over-the-top of seedlings and there was no soil incorporation for this treatment. Therefore, the material remained on the soil surface until rain washed into the soil. In this case, only the copper treatment produced a statistically significant effect. Although not statistically different from the controls, the lime plus copper treatment was intermediate between the lime-only treatment and the copper-only treatment. The copper treatment increased seedling height by 36 cm and increased groundline diameter by 7 mm (table 2). Tree form was affected on 91 percent of the untreated seedlings whereas 68 percent of the seedlings treated with copper had poor form. Needle symptoms were evident on 86 percent of the untreated seedlings and on 63 percent of the copper-treated seedlings.

Test 3: Treatments Applied Before Planting

Results were similar for Test 1. Both the copper treatment and the lime treatment increased seedling height and reduced plagiotropism. Untreated seedlings were about 187 cm tall compared with 219 cm tall for copper-treated seedlings (table 2). Seedlings treated with both copper and lime were 252 cm tall. Soil analyses indicated unamended soil had a pH of 3.95 (table 4) whereas soil with lime averaged a pH of 4.8 ($P > F = 0.0469$). The lime treatment increased calcium and magnesium to 443 and 165 ppm, respectively ($P > F \leq 0.017$). Phosphorus availability increased slightly to 7.4 ppm ($P > F = 0.0378$) as did chromium (0.25 ppm; $P > F = 0.0182$). No other nutrients were increased with the lime treatment.

Table 2—The effect of lime and copper on height and groundline diameter of loblolly pine seedlings

Treatment	Test 1	Test 2	Test 3	Test 1	Test 2
	- - - - - *height* (*cm*) - - - - -			- - *GLD* (*cm*) - -	
Control	67	73	187	2.8	3.4
Copper	88	109	219	3.3	4.1
Lime	91	73	220	3.3	3.3
Lime + copper	102	102	252	3.5	3.9

GLD = groundline diameter.

Table 3—The effect of lime and copper on deficiency symptoms of loblolly pine seedlings

Treatment	Test 1	Test 2	Test 3
	- - - - -*percent*[a]- - - - -		
Control	61	91	41
Copper	18	68	2
Lime	9	89	1
Lime + copper	13	68	2

[a] Percent of seedlings with copper deficiency symptoms.

Table 4—Soil analysis of control plots in Trial 3

Soil factor	Mean	Low value	High value
pH	3.95	3.9	4.1
OM[a] (*percent*)	3.9	1.9	4.7
CEC (*meq per l*)	6.6	4.1	7.7
Pb	4.4	2.8	5.9
K	13.6	7.0	17.6
Mg	43.4	17.8	56.5
Ca	83.0	25.4	118.3
Cu	0.18	0.0	0.7
Fe	11.3	5.8	13.9
Mn	2.3	1.1	3.3
Zn	0.5	0.1	0.8
B	0	0	0
Al	77.6	41.3	115.3
Ba	0.77	0.4	1.0
Co	0	0	0
Cr	0.025	0	0.1
Pb	0.35	0.3	0.4
Na	11.8	10.2	15.6

All elements are in ppm.
[a] OM = organic matter.

Future Research

Several factors likely contribute to the development of copper deficiency of pines on acid, sandy Coastal Plain soils. Fertilization with nitrogen or phosphorous can induce copper deficiency in some pines (Saur 1993, 1994; Turvey and Grant 1990). It seems quite likely that an application of diammonium phosphate prior to planting could induce copper deficiency on some acid podzoils (Saur 1990). Studies in Australia suggest nitrogen could be omitted at time of planting, and this may reduce copper deficiencies (Boomsma and others 1997). Studies should be conducted to determine if delaying fertilizer applications until the third year after planting could reduce the onset of symptoms. Although symptoms occurred without fertilization in Effingham County, the addition of nitrogen and phosphorous at planting likely increases the probability of copper deficiency occurring during the first year after planting.

CONCLUSIONS

After intensive site preparation, copper deficiencies can occur in loblolly pine and slash pine plantations on Leon and Mascotte soil groups in Georgia. Symptoms can be reduced by either applying copper sulfate at 36 kg per ha or by raising the soil pH with 6.7 metric tons of dolomite limestone. These treatments are more effective when incorporated into the soil prior to planting seedlings.

ACKNOWLEDGMENTS

We wish to thank Scott Cameron and Jody Burns for providing information on plageotropic seedlings in Echols and Effingham Counties.

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USE OF MINIATURE PLANTATIONS TO EXAMINE ACCELERATED STAND DEVELOPMENT IN LOBLOLLY PINE PLANTATIONS: SECOND YEAR RESULTS

Paul F. Doruska, Ralph B. Meeker, Jr., and Travis E. Posey[1]

Abstract—A miniature loblolly pine plantation was established in southeastern Arkansas in 2001. Two-month-old seedlings were planted in the spring of 2001 in a factorial arrangement of plots consisting of four within row spacings (10.2, 20.3, 30.5, and 50.8 cm) and four between row spacings (10.2, 20.3, 30.5, and 50.8 cm). Three replicates were installed. Half of the study was fertilized in February 2002 to incorporate fertilization into the experiment. To date vigor, root collar diameter, total height, and crown diameters in four directions have been measured five times. Fertilization has not had a significant effect on any of the attributes. Spacing did not have a significant effect on any attribute until the September 2002 measurement period, when the effect on root collar diameter and crown diameter was significant. By the January 2003 measurement, total height was also significantly affected by spacing.

INTRODUCTION

Loblolly pine (*Pinus taeda* L.) is the most commercially important tree species in Arkansas as well as the southern United States. As a result, much research has been devoted to measuring, quantifying, and modeling the growth and yield of such plantations (Baldwin and Cao 1999). Demand for forest products is increasing. Therefore, various management or silvicultural techniques are being studied and implemented in order to quantify any positive or negative effects on loblolly pine productivity. Two such techniques affecting productivity are fertilization (at planting or midrotation) and altered spacings at time of planting (planting density).

Over 600,000 ha of loblolly pine plantations in the southern United States were fertilized during the period 1976-1996. The number of ha given midrotation fertilization increased from 6,000 ha per year in 1988 to 81,000 ha per year in 1994 and to 162,000 ha per year in 1996 (NCSFNC 1995, NCSFNC 1997). Fertilization has an associated financial cost. Therefore, a multitude of fertilization studies have been implemented in the southeastern United States to quantify fertilization effects in those areas. Such information is crucial in order to make sound (biologically and economically) management decisions.

Plantation productivity can also be altered by employing different planting densities. Many studies are in place to examine these effects as well (Amateis and others 1988, Harms and Lloyd 1981, Haywood 1994, Liu and Burkhart 1994, Pienaar and Rheney 1996, Radtke and Burkhart 1999, Sterba and Amateis 1998). Ideally, an optimum density can be found to achieve optimal productivity for a given objective.

As with all avenues of scientific experimentation, new management or silvicultural techniques, as well as combinations of new techniques, will continually be proposed and examined. However, there exists one substantial drawback to performing such experiments with respect to loblolly pine plantation productivity: time to results. Almost all of the loblolly pine plantation research performed to date has been installed in full scale, or operational, plantations. Plantation development is determined by the combination of plant size and density. As a result, many of these studies can take 10 to 15 years before results are obtained, using typical plantation tree sizes and plantation densities.

Researchers have used scaled versions of experiments (Groninger and others 1995, Qiu and others 1992) in greenhouse environments to obtain research results in a more timely fashion. Such experiments typically last just one or two growing seasons. Amateis and others (2003) expanded the use of scaled experiments by using scaled loblolly pine plantations (hereafter referred to as miniature plantations) to examine spacing effects over a number of growing seasons and compared the results to more traditional, full scale plantation research. They chose to replicate through time instead of space. This project expands the groundbreaking work of Amateis and others (2003) by using miniature loblolly pine plantations replicated in space (and not over time) and by adding fertilization, in addition to spacing, as a factor in the experiment. Two-year results from the experiment are reported herein.

METHODS

The study site used in this project is located just outside of Monticello Arkansas, and is part of University of Arkansas-Monticello School of Forest Resources' university forest. The study area, dominated by juvenile loblolly pine and sweetgum (*Liquidambar styraciflua* L.) was cleared and tilled prior to planting. The soils in the area are mapped as a Calloway series with a Fine-silty, mixed, thermic Glossaquic Fragiudalf taxonomic classification. A hardpan is present at a depth of about 35 cm. Ditches were installed around the study area to allow drainage during the wet winters common to this area.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Genetically improved loblolly pine seeds were stratified and germinated in Jiffy® peat pellets during the 2000-2001 dormant season. At approximately 2 months of age, the seedlings (in the pellets) were planted at the research site. Seedlings were planted in plots (experimental units) consisting of a factorial arrangement of 4 within row spacings (10.2, 20.3, 30.5, and 50.8 cm) and 4 between row spacings (10.2, 20.3, 30.5, and 50.8 cm) resulting in 16 spacing combinations (or plot sizes). Each plot consisted of nine rows of nine seedlings, with the outer two rows in all directions serving as buffer trees. Therefore, just the interior 25 trees were used as observational units and averaged by plot for subsequent analysis.

Two fertilization levels (fertilized and non-fertilized) were also present within the experiment. Therefore, a complete replicate consisted of 16 spacing combinations and 2 fertilization levels, totaling 32 plots. Three replicates were installed, so a total of 96 plots were installed, and a total 7,776 seedlings were planted in the spring of 2001.

All plots were irrigated during the 2001 growing season and periodically treated with herbicide (sulfometuron methyl, 140 g ha^{-1}, and metsulfuron methyl, 35 g ha^{-1}) to control competition during the 2001 and 2002 growing seasons. Additionally, the plots were periodically treated with permethrin (290 ml ha^{-1}) to control Nantucket tip moth [*Rhyacionia frustrana* (Comstock)] during the 2002 growing season.

The study was first measured in January 2002, one growing season into the experiment and prior to fertilization (one time application of 200 kg ha^{-1} of a 11-40-6 fertilizer in late February 2002) and has been measured four times after fertilization, in April, June, and September of 2002 and January 2003 (two growing seasons into the experiment). At each measurement period, the following attributes were recorded for each observational unit: vigor (alive or dead) total height (to the nearest cm), root collar diameter (to the nearest 0.1 mm), and four crown diameters: within row, between row, and along the two diagonals (to the nearest cm). While other measures were taken, the aforementioned list is limited to those analyzed herein.

RESULTS AND DISCUSSION

Though the experiment allows examining all spacings formed by the factorial arrangement of 4 within row and 4 between row spacings (16 spacing combinations in all), the results from just the square spacings (10.2 x 10.2, 15.3 x 15.3, 30.5 x 30.5, and 50.8 x 50.8 cm) are reported herein. Since just the square spacings were analyzed, the four measured crown diameters for each seedling were averaged, and the average crown diameter was used in the analysis. Furthermore, only two replicates were used in the analysis herein as part of the third replicate was lost. All statistical tests were performed at $\alpha = 0.05$, and an arcsine transformation was applied to the survival percentages for all analyses.

Table 1 contains the p-values for the fertilization x spacing interaction for the respective factorial ANOVAs (one for each response: survival, root collar diameter, total height, and crown diameter). In all cases, the interaction term was insignificant. No p-value was reported for the January 2002 measurement as the study has yet to be fertilized.

In the absence of a significant fertilization x spacing interaction effect, each of the main effects: spacing [4 levels: (10.2 x 10.2, 15.3 x 15.3, 30.5 x 30.5, and 50.8 x 50.8 cm) and fertilization (two levels: fertilized and non-fertilized)] were examined. Table 2 contains the p-values for the respective spacing main effect tests by response and measurement date. Spacing began to significantly affect some of the measured responses by the summer of 2002, or about 1.5 years into the experiment. The spacing effect took longer to appear in this study when compared to that reported by Amateis and others (2003), though their spacings were slightly different.

The results for Tukey's honestly significantly different test of spacing effect for the September 2002 and January 2003 measurement periods are shown in table 3. As expected, pairwise differences of means were found only for effects deemed significant by the respective main effect F-tests (table 2). By January 2003, or two growing seasons into the experiment, separation between the tightest spacing (10.2 x 10.2 cm) and the widest spacing (50.8 x 50.8 cm)

Table 1—P-values of spacing x fertilization interaction tests by measurement date from the factorial ANOVAs

Response	01/2002	04/2002	06/2002	09/2002	01/2003
Survival	N/A	0.0667	0.0722	0.4564	0.4303
Root collar diameter	N/A	0.8320	0.8155	0.9364	0.8294
Total height	N/A	0.6421	0.3272	0.7905	0.6403
Crown diameter	N/A	0.3909	0.1767	0.4209	0.6428

Table 2—P-values of the spacing main effect tests by measurement date from the factorial ANOVAs

Response	01/2002	04/2002	06/2002	09/2002	01/2003
Survival	0.6432	0.1154	0.1638	0.8342	0.3996
Root collar diameter	0.1676	0.4232	0.3512	0.0031	< 0.0001
Total height	0.1789	0.4232	0.2651	0.0706	0.0217
Crown diameter	0.5964	0.2065	0.0596	< 0.0001	< 0.0001

Table 3—Means and Tukey's honestly significantly different test results for the spacing effect from the September 2002 and January 2003 measurement periods by response

Response	Spacing	09/2002	01/2003
	cm x cm		
Survival(%)	10.2x10.2	91a[a]	81a
	20.3x20.3	91a	81a
	30.5x30.5	92a	91a
	50.8x50.8	95a	90a
Root collar diameter (*mm*)	10.2x10.2	5.89a	6.96a
	20.3x20.3	6.79ab	8.45ab
	30.5x30.5	7.04ab	9.16ab
	50.8x50.8	8.67ab	12.15c
Total height (*cm*)	10.2x10.2	30.88a	34.38a
	20.3x20.3	32.20a	35.10a
	30.5x30.5	33.22a	36.53a
	50.8x50.8	40.19a	45.90b
Crown diameter (*cm*)	10.2x10.2	17.04a	18.59a
	20.3x20.3	21.89ab	25.19ab
	30.5x30.5	23.94ab	24.64ab
	50.8x50.8	28.76b	33.71b

[a] Means sharing a common letter within respective response and measurement dates combinations are not significantly different at $\alpha = 0.05$.

was apparent with the tightest spacing resulting in significantly lower responses for all attributes except survival.

Table 4 contains the p-values for the fertilization main effect F-tests from the respective factorial ANOVAs. None of these F-tests was significant. Recall that fertilizer was applied one time at a rate about equal to that of full scale plantations. Perhaps the rate was too low to warrant a significant response given the increased planting density of this study compared to full scale, or operational, plantations.

CONCLUSIONS

This experiment, to date, corroborates the findings of Amateis and others (2003). Scaled, or miniature, loblolly pine plantations can be used to shorten the time necessary to obtain significant spacing effects. Interestingly, a longer length of time was required to obtain significant spacing effects in this experiment than that of Amateis and others (2003). This may be the result of the different spacings used between the studies (slightly wider spacings were used in this study) or the nature of replication used: space in this study versus time in Amateis and others (2003). The slight site to site variation present in this study may be impacting the results herein. Future analysis will include examining the use of site covariates. Interestingly, such variation could be avoided by using the same site repeatedly over time as in Amateis and others (2003). However, this can lend itself to climatic differences from replication to replication, something that is avoided by replicating in space instead of time.

The fertilization effect was not significant two growing seasons into the experiment (or one growing season after application). In retrospect the fertilization rate used might have been too low to warrant a response. Future applications will be at a higher rate.

ACKNOWLEDGMENTS

The authors thank both the Arkansas Agricultural Experiment Station Research Incentive Program and the Arkansas Forest Resources Center for providing funding for this endeavor and International Paper Company for donating the seed used herein. The assistance of Aaron Dick, Raju Gadtoula, Matt Lane, Doug Marshall, Alan Procell, and Tim Sidour at time of planting is also acknowledged. This manuscript is approved for publication by the Director of the Arkansas Agricultural Experiment Station.

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Table 4—P-values of the fertilization main effect tests by measurement date from the factorial ANOVAs

Response	01/2002	04/2002	06/2002	09/2002	01/2003
Survival	N/A	0.1197	0.1607	0.2315	0.2408
Root collar diameter	N/A	0.5169	0.7119	0.5278	0.3810
Total height	N/A	0.2542	0.5110	0.5801	0.4222
Crown diameter	N/A	0.4495	0.8024	0.4070	0.3177

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OLD-FIELD THINNED LOBLOLLY PINE PLANTATION FERTILIZATION WITH DIAMMONIUM PHOSPHATE PLUS UREA AND POULTRY LITTER – 4 YEAR GROWTH AND PRODUCT CLASS DISTRIBUTION RESULTS

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Abstract—A study area was installed in the Coastal Plain of South Carolina to determine the effects of diammonium phosphate (DAP) plus urea and poultry litter fertilization on growth, yield, diameter distributions, and product class distributions in an old-field (Norfolk soil) thinned loblolly pine (*Pinus taeda* L.) plantation. Treatments included: (1) control = no fertilization, (2) 125 DAP + 385 pounds urea per acre and (3) 7 tons per acre of broiler litter and were applied in the spring of 1998. The loblolly stand prior to thinning was highly stocked with an average of 750 trees per acre (TPA) and a basal area (BA) of 150 square feet per acre by the end of the tenth growing season. The stand was thinned back to 250 TPA and 50 square feet per acre basal area in January 1998. Mean d.b.h., basal area per acre and total heights were not significantly different between treatments prior to treatment and 4 years after treatment (YAT). Four YAT, the broiler litter treatment had a greater loblolly pine d.b.h. growth increment (2.5 inches) than the DAP+urea (1.9 inches) and the control (1.8 inches). Merchantable volumes for the control, DAP+urea, and broiler litter treatments were not significantly different 4 YAT. Chip and saw volume per acre growth increment (d.b.h. > 8.5 inches) for the broiler litter treatment (1,030 cubic feet per acre) was 42 percent greater than the control and 44 percent greater than the DAP+urea 4 YAT.

INTRODUCTION

South Carolina's forest and poultry industries are important to the State. Forest land application of poultry litter is a viable alternative for litter utilization in South Carolina and other Southern States. However, many nonindustrial private forest (NIPF) landowners question the benefit of poultry litter application in pine plantations compared to traditional inorganic fertilizer materials. The objectives of this study were to (1) determine old-field loblolly pine (*Pinus taeda* L.) growth response and (2) product class distribution changes as a function of a one-time poultry litter compared to a common operational diammonium phosphate (DAP), (18-46-0) plus urea (46-0-0) application and no fertilizer treatment after the stand was thinned.

METHODS

The study area was an old-field planted loblolly pine plantation located in Clarendon County, SC in the Atlantic Coastal Plain physiographic region. The soil was mapped as the Norfolk soil series (fine-loamy, Typic Kandiudults). The entire plantation was thinned at the end of the tenth growing season from 750 trees per acre (TPA) and 155 square feet per acre basal area to 250 TPA and 50 square feet per acre basal area in January 1998. The experimental design was complete block with three replications per treatment. The treatments were: (1) control = no fertilizer materials, (2) 125 pounds DAP plus 385 pounds urea per acre [200 N + 25 P per acre], and (3) 7 wet tons poultry litter per acre. The latter treatment level (table 1) gave a similar plant available nitrogen (N) level as the N in the DAP and urea. Nine internal permanent measurement plots (IPMP), (1/4 acre) were installed in the center of each the gross treated plot (1/2 acre). Forty feet of untreated buffer were maintained between all plots. All living trees in each IPMP were tagged, numbered, and measured for d.b.h (diameter tape) and total height (initially with a height pole and subsequently with a laser hypsometer) prior to treatment. Sampling was conducted in February 1998 to establish baseline soil (0-6 inches using 1-inch diameter soil probe at 10 random locations per plot) and foliar (3 dominant trees per plot, upper 1/3 crown, south side, first flush of previous year's growth) nutrient status. Post-treatment soil and foliage samples were collected during the winter on a biennial basis. The DAP and urea were applied by a granular spreader truck

Table 1—Poultry (stacked broiler litter) litter characteristics and application level from a 7 tons per acre application to an old-field thinned loblolly pine plantation at age 11-year-old in Clarendon County, SC

Component	Concentration	Application level
	percent	*pounds per acre*
Total-N	2.86	400.00
NH4-N	0.36	50.40
Organic-N	2.50	350.00
Available-N[a]	1.72	240.00
P_2O_5	2.64	370.00
K_2O	2.29	321.00
Ca	2.09	293.00
Mg	0.39	54.60
S	0.45	63.00
Cu	0.03	4.38
Zn	0.03	4.24

[a] Available-N = 60 percent of organic-N and ammonium-N is estimated to plant available when surface applied in the first growing season.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Table 2—Soil (0-6 inches) nutrient status prior to treatment and 4 years post-treatment in the old-field thinned loblolly pine plantation in Clarendon County, SC

Treatment	pH	P	K	Ca	Mg	Cu	B
				ppm			
			1998				
Control	5.5	9	21	253	29	0.6	0.1
Fertilizer	5.8	12	20	281	30	0.5	0.1
Litter	5.8	2	24	348	44	0.5	0.1
			2002				
Control	5.8	3b [a]	16b	230b	25b	0.05b	0.05
Fertilizer	5.6	13ab	12b	201b	21b	0.05b	0.05
Litter	5.8	28a	38a	393a	55a	0.60a	0.20

[a] Nutrient treatment means within the same year followed by a different letter indicate significant differences at the $\alpha = 0.05$ level using Duncan's Multiple Range Test.

on April 28,1998 and the broiler litter was applied on June 8 and June 9, 1998 with a tractor and pull behind side port spreader. Both fertilizer materials were planned to be applied at the same time, but the broiler litter could not be applied until a tractor and spreader became available. All living trees were remeasured for d.b.h. and total height in March 2000 and March 2002. A volume equation for loblolly pine by Bailey and others (1985) was used to estimate merchantable volume (3-inch top inside bark, cubic feet) per acre, pulpwood volume (4.6 inches $\leq$ d.b.h $\geq$ 8.5 inches), and chip-and-saw volume (d.b.h. > 8.5 inches) per acre. Growth parameter means by treatment were compared statistically using Duncan's Multiple Range Test at the $\alpha = 0.05$ significance level.

RESULTS

Foliar N, P, K, Ca, Mg, B, and Cu nutrient status and soil extractable-P levels were at or above sufficiency for loblolly pine (Allen 1987, Pritchett and Comerford 1983, Wells and others 1973) in the study area prior to DAP+urea and poultry litter application (tables 2 and 3) except for soil extractable P in the poultry litter plots. There were no significant differences between treatment means for d.b.h, basal area, or total height during the 4 year study period (table 4). Trees per acre were initially not significantly different. The poultry litter treatment had significantly fewer TPA than the control 4 YAT. Four year mortality was 6.5 percent for the control, 11 percent for the DAP+urea, and 14.5 percent for the poultry litter treatment. Four year d.b.h. growth increment from the broiler litter treatment was greater (2.5 inches) than the control (1.8 inches) and DAP+urea (1.9 inches).

Table 3—Foliar nutrient status prior to treatment and 4 years post-treatment in the old-field thinned loblolly pine plantation in Clarendon County, SC

Treatment	N	P	K	Ca	Mg	Cu	B
			percent			*ppm*	
			1998				
Control	1.4	0.12	0.41	0.23	0.11	2.5	17
Fertilizer	1.3	0.12	0.40	0.24	0.13	2.7	16
Litter	1.4	0.12	0.41	0.31	0.14	3.2	21
			2002				
Control	1.3	0.12	0.43	0.22	0.14	3.5	13
Fertilizer	1.5	0.13	0.45	0.22	0.14	3.2	11
Litter	1.5	0.12	0.43	0.33	0.15	3.2	14

There were no significant differences in merchantable volume (3-inch top inside bark) per acre or chip-and-saw volume (d.b.h > 8.5 inches to a 6-inch top inside bark) per acre (table 5). The poultry litter treatment had significantly less pulpwood volume (d.b.h of 4.5 through 8.5 inches to a 3-inch top inside bark) 2 YAT (year 2000) than the control and DAP+urea treatments. This pulpwood trend of less pulpwood volume for the poultry litter compared to the control and DAP+urea continued 4 YAT but the treatments

Table 4—Pre-treatment (1998), 2 (2000), and 4 (2002) year post-treatment growth parameter means in an old-field thinned loblolly pine plantation in Clarendon County, SC

	Diameter			Basal area			Height		
Treatment	1998	2000	2002	1998	2000	2002	1998	2000	2002
	inches			*square feet per acre*			*feet*		
Control	6.2	7.2	8.0	56.4	75.7	87.9	32.2	36.7	41.2
Fertilizer	6.1	7.2	8.0	53.5	72.8	82.3	35.6	38.8	43.7
Poultry litter	6.2	7.6	8.7	54.5	73.0	90.8	32.6	37.2	41.8
P-value	0.846	0.338	0.077	0.843	0.844	0.395	0.170	0.643	0.611

Table 5—Pre-treatment (1998), 2 (2000), and 4 (2002) year post-treatment volume means in an old-field thinned loblolly pine plantation at age 11-years-old in Clarendon County, SC

	Merchantable volume			Pulpwood volume[a]			Chip and saw volume		
Treatment	1998	2000	2002	1998	2000	2002	1998	2000	2002
	cubic feet per acre								
Control	813	1250	1607	795	917a	717	14	269	738
Fertilizer	846	1283	1609	826	985a	727	15	243	731
Poultry litter	800	1225	1692	749	646b	435	41	474	1071
P-value	0.920	0.936	0.880	0.779	0.007	0.235	0.173	0.292	0.351

[a] Treatment means followed by a different letter indicate significant differences at the α = 0.05 level using Duncan's Multiple Range Test.

means were not significant. Chip-and-saw volume 4 year growth increment for the poultry litter treatment (1,030 cubic feet per acre) was 42 percent greater than the control (724 cubic feet per acre) and 44 percent greater than the DAP+urea (716 cubic feet per acre).

DISCUSSION

Trees per acre mortality differences over the 4 year study period may have occurred due to an annosum root disease [*Heterobasidion annosum* (Fr.) Bref.] problem on the edge of the poultry litter and DAP+urea plots in replications two and three. This problem appears to have dissipated 4 YAT. Whether the poultry litter and DAP+urea fertilization increased the annosum root disease spread, thereby increasing mortality over the control, is not known.

A common loblolly response to N+P fertilization using DAP+urea is approximately 60 cubic feet per acre per year volume increase lasting 5 to 8 years (NCSUFNC 1998). The negligible response to the DAP+urea treatment may have been due to at least three factors: (1) an application timing problem, (2) foliar nutrient status was sufficient, and (3) greater mortality (11 percent) compared to the control (6.5 percent). Kissel and others (2001) noted that ammonia volatilization losses can be substantial in closed canopy loblolly pine stands when air temperature and relative humidity are high. Twenty-five days lapsed between the time of DAP+urea treatment and the first substantial rain (> ½-inch) in the study area with temperatures and relative humidity that were higher than the historic average for the area. In contrast, a ¾-inch rain occurred 1 hour after the last poultry litter plot was treated on June 9, 1998. Another plausible explanation to the lack of response to DAP+urea fertilization is indicated by the soil extractable-P levels (table 2) and foliar N and P (table 3) concentrations being above the minimum guidelines (Allen 1987, Pritchett and Comerford 1983, Wells and others 1973) for a significant fertilization response to occur in the DAP+urea plots.

Statistically, there were few treatment mean differences 4 YAT; however there were two important trends that occurred. Mean d.b.h. 4-year growth increment for the poultry litter plots (2.5 inches) was 32 percent greater than the DAP+urea (1.9 inches) and 39 percent greater than the control (1.8 inches). Chip-and-saw (CNS) volume for the poultry litter treatment was over 300 cubic feet per acre greater than the control and DAP+urea 4 YAT. The 4 YAT pulpwood volume increment decrease for the poultry litter treatment was 236 cubic feet per acre less than the control and 215 cubic feet per acre DAP+urea 4 YAT (table 5). Therefore, while the merchantable volume for the poultry litter treatment was not significantly greater than the control, product class distribution changes were more dramatic in the poultry litter treatment than the control due to the 0.70 inch d.b.h. growth increase 4 YAT.

Economically, applying South Carolina third quarter 2002 stumpage prices (TMS 2002) of $14 per cord for pulpwood and $58 per cord for CNS (86 cubic feet per cord wood+bark), the poultry litter treatment volume per acre value ($793) was 30 percent greater than the control ($610) and DAP+urea ($611) treatment 4 YAT. Using a common South Carolina $10 per ton cost for the litter and application and the revenue gain of $193 per acre between the poultry litter and control, the internal rate of return $[(193/70)^{1/4} - 1]$ for the poultry litter treatment is 28.8 percent for the extra wood grown 4 YAT.

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THE EFFECT OF LARGE APPLICATIONS OF NUTRIENTS FROM ORGANIC WASTE ON BIOMASS ALLOCATION AND ALLOMETRIC RELATIONS IN LOBLOLLY PINE

Scott D. Roberts, Alexander L. Friend, and Patrick D. Gerard[1]

Abstract—We applied broiler litter to an 8-year-old precommercially thinned loblolly pine (*Pinus taeda* L.) stand at 0, 5.6, and 23 Mg ha^{-1}, supplying 0, 200, and 800 kg N ha^{-1}. A destructive harvest was implemented two growing seasons following litter application to evaluate treatment impacts on patterns of aboveground biomass allocation and to develop allometric functions enabling prediction of aboveground biomass components. We examined relative allocation to foliage, crown wood, and stemwood; and the proportion of current-year and second-year foliage in the upper vs. the lower crown. No treatment effects were observed in general allocation patterns between foliage, crown wood, and stemwood mass, although treatments did significantly increase the ratio of current-year to second-year foliage in the upper crown. Biomass allocation patterns within trees did vary with tree size. The ratio of foliage to woody biomass remained similar across the range of tree sizes examined; but within the woody component, the amount of crown wood relative to stemwood increased with tree size. The ratio of current-year to second-year foliage remained similar in the lower crown, but the proportion of second-year foliage in the upper crown increased with d.b.h. Statistically significant treatment differences were found in the allometric relationships for estimating stemwood, crown wood, and foliar biomass. In all cases, litter application treatments increased the slope of the relationship between the aboveground biomass component and tree size. Our results suggest that failure to account for treatment-related effects on tree allometry could result in estimation errors of 5-15 percent for individual aboveground biomass components.

INTRODUCTION

As human populations increase, the disposal of human generated waste – municipal, industrial, and agricultural – is becoming more of a problem. One option increasingly being considered is the spreading of waste on agricultural or forested lands (Dickens 2002, Endale and others 2002, Shepard 2000, Vance 1996). One major source of agriculturally-generated waste is confined animal feeding operations. For example, poultry production in the Southeastern United States, one of the regions major agricultural activities, raises over 6.2 billion broilers chickens annually with a production value of over $12.3 billion (U.S. Department of Agriculture 2002). Production is concentrated in densely populated chicken houses, resulting in tremendous amounts of litter. In 1998, for example, an estimated 12 million metric tons of poultry litter was produced nationally (Endale and others 2002). The litter generated in poultry production is rich in nitrogen (N) and phosphorus (P). The primary disposal mechanism, historically, has been application to pastureland as an organic fertilizer (Endale and others 2002, Sauer and others 1999). However, years of repeated applications have resulted in elevated soil P levels and concerns over the potential effects of nutrient-rich runoff on water quality (Sauer and others 1999, Sims and Wolf 1994).

As an alternative to pasture application, some are looking at the abundant pine forests of the South as an option for litter disposal (Beem and others 1998, Samuelson and others 1999). Fertilization research has shown that nutrient limitations occur on many southern pine stands and growth often responds positively to added nutrients (Allen and others 1990). However, little research has investigated the ability of pine stands to contain the nutrients in poultry litter on site and the effects that added nutrients in the litter would have on tree growth and development. An increase in net primary production is expected to result from the added nutrients in poultry litter; however, questions remain as to how that increased growth will be distributed within the trees. The ability to predict the amount and distribution of growth is important for a variety of reasons, including the estimation and modeling of total biomass increases. Examination of the influence of treatments on biomass distribution is commonly accomplished by testing for significant treatment effects on allometric equations (Barclay and others 1986, Gower and others 1993, Grier and others 1984, Naidu and others 1998).

In the fall of 1999, we initiated a study to examine responses in a loblolly pine (*Pinus taeda* L.) stand to a one-time large application of poultry litter. The overall objectives of this study were to investigate the ability of loblolly pine forests to contain a large, one-time application of poultry litter and to investigate the extent to which the litter will enhance tree growth. In this paper, we report on a portion of the study in which destructive sampling was used 2 years after treatment to evaluate whether litter application affected tree allometric relationships and thus the distribution of aboveground biomass.

METHODS

The study was located in Newton County, MS on the Mississippi State University Coastal Plain Branch Station (32°20'N, 89°04'W). Average annual daily high and low temperatures at the site are *ca*. 24° and 11 °C, respectively. Average annual precipitation is *ca*. 1,400 mm. Soils on the study site are a fine sandy loam in the Shubuta Series,

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

taxonomically classified as a fine, mixed, thermic Typic Paleudults (Ultisols). The study was established in an 8-year-old loblolly pine stand that was initiated as a plantation following a clearcut harvest but, due to heavy natural regeneration, contained over 4,000 trees per acre.

Nine 20 m x 20 m treatment plots were established and thinned to a basal area of 11 m^2 ha^{-1}. Within each treatment plot, a 10 m x 10 m measurement plot was established containing between 27 and 56 trees. In March 2000, poultry litter in the form of stock-piled cake collected from a local broiler operation near Newton, MS, was applied to the plots. At the time of application, litter moisture content was 21 percent. The elemental composition of the litter on a dry weight basis was 38 percent C, 4.3 percent N, 2.0 percent P, 3.2 percent K, 2.8 percent Ca, 0.7 percent Mg, 0.6 percent S, 590 ppm Zn, 60 ppm B, 680 ppm Mn, Fe 987 ppm Fe, and Cu 969 ppm Cu. Litter was applied at three treatment rates to three plots each in a completely randomized design. The three treatment rates were 0 Mg ha^{-1} (N_0 = Control), 5.6 Mg ha^{-1} (N_{200}), and 23 Mg ha^{-1} (N_{800}). Application rates were based on the N assay of the litter to supply *ca*. 0, 200, and 800 kg N ha^{-1}, respectively. The N_{200} treatment was designed to add N at approximately the same rate as would typically be applied in an operational commercial fertilization. This resulted in adding approximately 2-3 times more P than would typically be applied operationally. The three treatments resulted in P applications of ca. 0, 92, and 370 kg P ha^{-1}.

Trees on each measurement plot were measured pretreatment and bi-monthly thereafter for stem diameter at breast height (d.b.h.) (1.37 m) and total height (HT). Height to the base of the live crown (HT_{blc}) was measured annually. Beginning in May 2000, understory vegetation was controlled annually with herbicides. Destructive sampling took place between Aug. 25 and Sept. 8, 2001. Twenty-seven trees were sampled, nine from each of the three treatments. Trees were harvested from the treated buffer surrounding each measurement plot and were selected to represent the range of sizes found across the plots. Prior to felling, each tree was measured for dbh, HT, and HT_{blc}. Each tree was felled at ground level and the stem divided into 1-m sections. Within the crown, branches were removed separately from each section and separated into current year foliage and twigs, previous year foliage and twigs, and non-foliated branch portions. Total fresh weight of each component was recorded, and a random subsample was weighed fresh and retained for laboratory analysis. With all the branches removed, the main stem was cut into 1-m sections. Outside bark diameter and bark thickness were measured at the bottom of each section, and total fresh weight of each stem section was recorded. A 3-4 cm thick disk was removed from the base of each section, its fresh weight was recorded, and the disk retained for laboratory analysis. In the laboratory, all subsamples were dried at 80 °C to a constant weight and weighed to determine fresh mass:dry mass ratios for each component of each section. Foliage was separated from twigs to determine foliage mass:wood mass ratios. Fresh mass:dry mass ratios and foliage mass:wood mass ratios were used to determine the total dry mass of each aboveground biomass component of the tree.

Results from the destructive sampling were analyzed for size and treatment related differences in aboveground biomass allocation. Analysis of covariance was performed using the MIXED model procedure in the Statistical Analysis System (SAS Institute Inc., Cary, NC, Release 8.1). The model included a random plot effect, with d.b.h. as the covariate, to examine size related differences in biomass distribution. We looked for differences in relative allocation to stemwood (including bark), crown wood, and foliage biomass. We also tested for differences in the relative proportions of first-year foliage and second-year foliage, and whether they differed between the upper crown and the lower crown.

Because allocation patterns in trees naturally differ with tree size, differences in allocation patterns were assessed by comparing allometric functions relating biomass components to measures of tree size. Nonlinear equations were developed for estimating aboveground biomass components using the NLMIXED procedure in SAS. Indicator variables were included in the model to test for treatment effects on the allometric relationships. The general model form was:

$$Y = (\varepsilon_1 + b_0 + b_1 I_{200} + b_2 I_{800}) \cdot X^{(b3 + b4 \cdot I200 + b5 \cdot I800)} + \varepsilon_2 \quad (1)$$

where Y is the biomass component, X = [d.b.h.^{2} x HT (D^2H)] when Y = stemwood or crown wood mass and X = d.b.h. when Y = foliage components, I_{200} and I_{800} are indicator variables for treatments N_{200} and N_{800}, respectively, b_0-b_5 are fitted regression coefficients, ε_1 is a random error term for plot-to-plot variation, and ε_2 is a random error term for tree-to-tree variation. A critical value of $\alpha = 0.10$ was used in all analyses for determining significance.

In addition to testing for treatment differences in allometric relationships within individual trees, we wanted to know how much difference treatment specific allometric relationships would have on stand-level estimates of aboveground biomass. We generated biomass estimation equations both with and without treatment effects in the model. Equations without treatment effects were derived from the NLMIXED model where I_{200} and I_{800} were 0 (i.e., control trees only). The equations were applied to tree data from each plot to develop total per hectare biomass estimates of all aboveground tree components. The two sets of estimates were compared to examine treatment differences in estimates of aboveground biomass components.

RESULTS

There were size-related differences in proportional aboveground biomass allocation (fig. 1). The MIXED model results showed that relative allocation to stemwood decreased with dbh ($P < 0.0001$, fig. 1a), while allocation to crown wood increased with dbh ($P < 0.0001$, fig. 1b). Proportional allocation to foliage also increased with dbh (fig. 1c), but these values were much more variable and the relationship was not as strong ($P = 0.006$) as with the woody components.

Proportional allocation between stem, branches, and foliage did not differ significantly among treatments. On average, 70.1 percent of aboveground biomass was

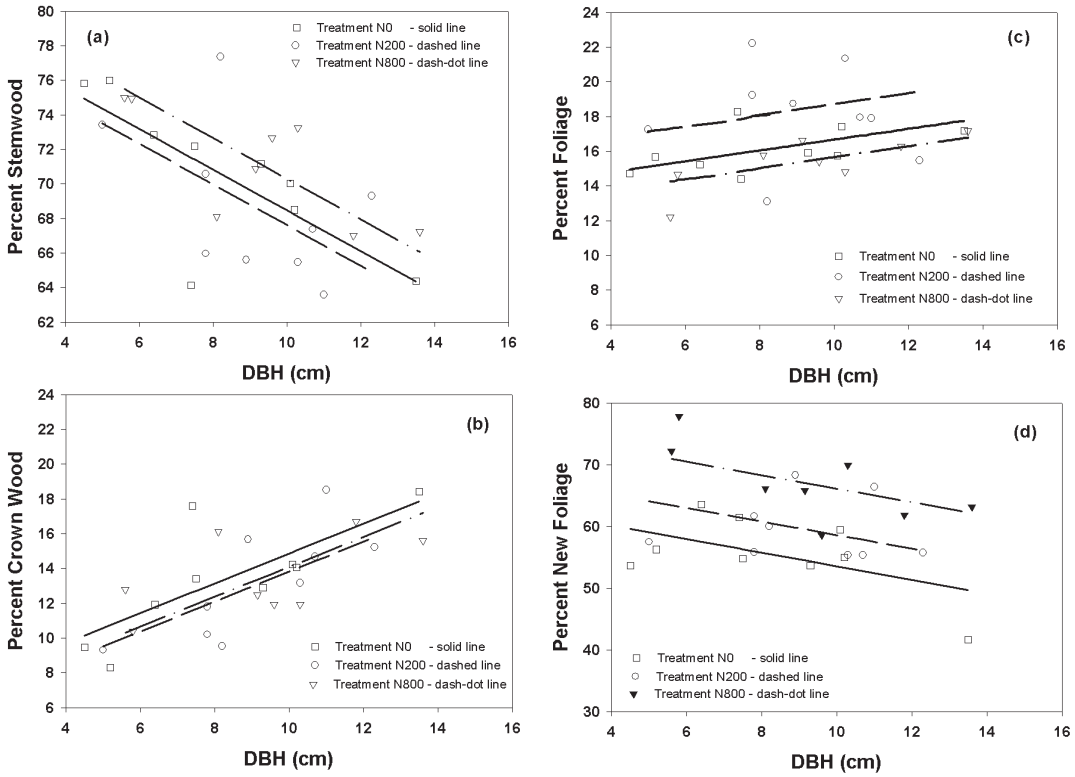

Figure 1—Tree size adjusted differences in percent aboveground biomass allocation to (a) stemwood, (b) crown wood, (c) total foliage, and (d) new foliage for three treatment levels of poultry litter application to an 8-year-old loblolly pine stand. Relationships developed from 26 trees destructively sampled near Newton, MS two growing seasons following litter application.

allocated to stemwood, 13.3 percent to crown wood, and 16.6 to foliage, although again, these values varied with tree size. One factor that did differ by treatment was the proportion of current year foliage (new foliage:total foliage) (P = 0.0078; fig. 1d). Approximately 55 percent of foliage in the control treatment (N_0) was new, compared to nearly 60 percent in treatment N_{200} and over 67 percent in treatment N_{800}. All of these values differed significantly from each other.

Treatment differences in the percent current-year foliage occurred primarily in the upper crowns, where treatments N_{200} and N_{400}, with 70.2 percent and 73.8 percent new foliage, respectively, had a significantly higher proportion of new foliage than treatment N_0, which only had 60.1 percent new foliage. In the lower crowns, the percent current-year foliage did not differ significantly between treatments, although the average percentage for N_{800} was 7-8 percent higher than in the other two treatments.

Results from the NLMIXED model suggest significant treatment effects on allometric relationships for all of the aboveground biomass components examined (fig. 2). Treatments significantly affected the relationship between stemwood biomass and D^2H (P = 0.0443). The differences were between the treated plots and the controls – there were no significant differences between treatments N_{200} and N_{800} (fig. 2a). Figure 2a shows a steeper relationship between stemwood biomass and D^2H in the two fertilization treatments than in the control.

The relationship between crown wood biomass and D^2H was also significantly affected by the treatments (P = 0.0242; fig. 2b). Again, the significant differences were between the treatments and the control, with no differences between treatments N_{200} and N_{800}. Figure 2b again shows a steeper relationship between crown wood and D^2H in the two active treatments than in the control.

The relationship between total foliage and d.b.h. again showed significant treatment effects (P = 0.0224; fig. 2c), with no difference between the active treatments. Once again, the relationship between total foliage and d.b.h. was steeper for trees from the active treatments. This same pattern holds for the relationship between the total amount of new foliage and d.b.h. The treatment effect is not as strong (P = 0.0864; fig. 2d) but is still significant; and there is no significant difference between the active treatments. The relationship between new foliage and d.b.h. was again steeper for trees from the treated plots. The only relationship examined where there was not a significant treatment effect was between the total amount of old foliage and d.b.h. (P = 0.3767, fig. 2e).

DISCUSSION

Treatment-related differences in the amount and distribution of aboveground biomass can result from two sources. One is accelerated tree growth and stand development that may occur due to treatments. Larger trees allocate biomass differently than smaller trees. The other is through treatment effects on how trees allocate aboveground

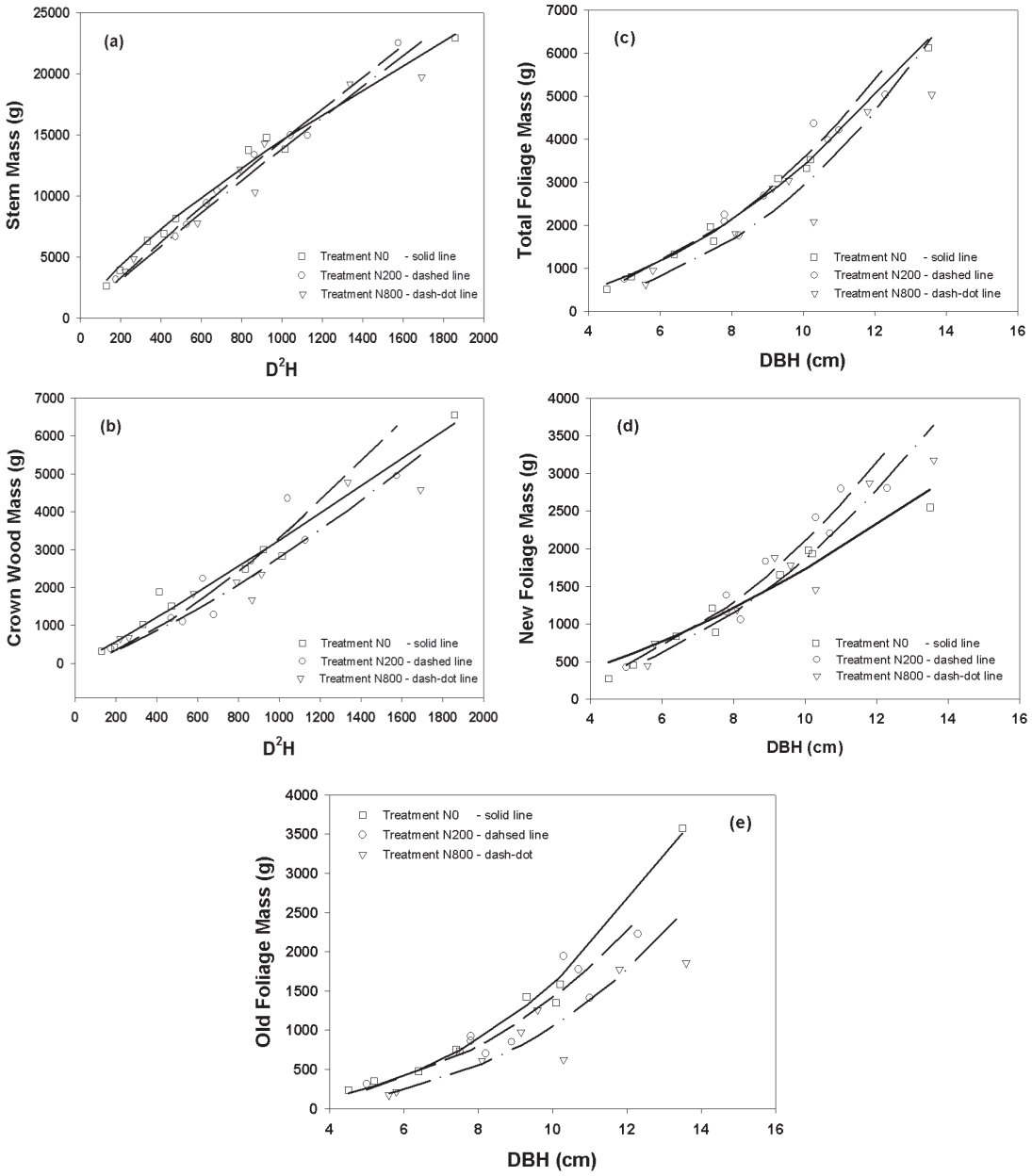

Figure 2—Allometric relationships between tree size and (a) stemwood mass, (b) crown wood mass, (c) total foliage mass, (d) new foliage mass, and (e) old foliage mass for three treatment levels of poultry litter application to an 8-year-old loblolly pine stand. Relationships developed from 26 trees destructively sampled near Newton, MS two growing seasons following litter application.

growth, that is, through changes in allometry. We observed both effects in this study. In every case where we found significant treatment effects in allometric relationships, the differences were between the treated plots and the control plots. On plots where poultry litter was applied at either 5.6 or 23 Mg ha^{-1}, no differences in tree allometries were observed. In all cases where significant differences were observed, the slope of relationship between the estimated biomass component and the measure of tree size was steeper on the treated plots than on the control plots. This implied that for a given incremental increase in tree size, treated trees added more biomass than untreated trees.

To better illustrate the potential importance of the treatment related effects, we compared the predicted mass of aboveground biomass components calculated from allometric equations that included treatment effects to the predicted mass calculated from equations that did not include treatment effects (table 1). Separate models generated in the NLMIXED model for the N_{200} and N_{800} treatments were used, although these treatments did not differ significantly. When treatment effects were not included in the model, estimates of stemwood and total foliage mass were generally higher than when treatments were considered, and estimates of crown wood and new foliage mass were generally less than when treatments were considered.

Table 1—Comparison of predicted mass of aboveground components derived from allometric equations with and without effects of poultry litter application on allometric relationships[a]

Component treatment	Predicted mass without treatment effects included	Predicted mass with treatment effects included	Difference (without treatment—with treatment)
	Mg ha^{-1}		*percent*
Stemwood			
N_0	33.10		N/A
N_{200}	37.09	35.19	+5
N_{800}	37.19	34.69	+7
Crown Wood			
N_0	6.11		N/A
N_{200}	7.61	7.41	+3
N_{800}	6.90	8.07	-15
Total Foliage			
N_0	7.71		N/A
N_{200}	8.93	9.19	-3
N_{800}	9.12	7.83	+16
New Foliage			
N_0	4.47		N/A
N_{200}	4.85	5.48	-11
N_{800}	4.76	5.02	-9

[a] Separate equations were used to predict component biomass for treatments $N2_{00}$ and N_{800}, even though statistical analysis showed no significant differences in the allometric relationships between these treatments.

Our analysis showed that failure to account for treatment effects could result in overestimating stemwood and total foliage mass and underestimating crown wood and new foliage mass. These estimation errors, generally in the 5-15 percent range, could significantly alter estimates of total aboveground biomass, as well as factors such as leaf area index and the distribution of aboveground nutrient pools.

ACKNOWLEDGMENTS

Approved for publication as Journal Article No. FO-230 of the Forest and Wildlife Research Center, Mississippi State University.

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EFFECTS OF FERTILIZATION ON THE VEGETATION DYNAMICS OF YOUNG LOBLOLLY PINE PLANTATIONS

Ryan McKnight and Eric Heitzman[1]

Abstract—We examined growth of loblolly pine (*Pinus taeda* L.) and non-pine vegetation in three 4- to 6-year-old plantations in Arkansas, Mississippi, and Louisiana that were fertilized with varying rates of N and P. Two years after treatment, pine d.b.h. growth had generally increased with fertilization rate, with significant differences in Arkansas and Mississippi. Pine height growth was more variable with no significant differences by treatment. Significant differences in leaf area index were observed in Mississippi and Louisiana. At two sites, non-pine woody biomass was significantly greater at higher fertilization rates. However, there were no significant differences in total biomass of non-pine vegetation at any of the study areas. The limited differences between treatments may be due to drought, an ice storm, the short-term nature of our study, an insufficient number of biomass plots, and/or crown closure at one of the study sites.

INTRODUCTION

Midrotation fertilization of loblolly pine (*Pinus taeda* L.) plantations has become a common silvicultural practice throughout the Southern United States. Field trials established by the North Carolina State Forest Nutrition Cooperative (NCSFNC 1997,1998), as well as growth and yield models developed from fertilized midrotation stands (Amateis and others 2000, Hynynen and others 1998), indicate that midrotation pine plantations are responsive to single applications of nitrogen (N) and phosphorus (P). As a result, over 280,000 ha of established pine plantations were fertilized in 2001 with 224 kg per ha N and 28 kg per ha P (NCSFNC 2002a). This prescription has proven ecologically and economically attractive to the forest industry; over the next 8 years, this $50 million investment in fertilization is predicted to result in an increase in wood yield of almost 27,000 kg per ha.

Given the successful application of midrotation treatments, research activities have expanded to include fertilizing earlier in the rotation. For example, the most recently established NCSFNC field trial, Regionwide (RW) 18, is designed to identify optimal rates and frequencies of fertilization in relatively young (3- to 7-year-old) pine plantations (NCSFNC 2000, 2001, 2002b). Consequently, treatments in RW 18 stands generally begin before or at time of canopy closure and include previously untested fertilizer rates and frequencies.

From a silvicultural perspective, the RW 18 field trial is a novel approach because it examines fertilization as a treatment to be applied throughout a rotation. However, one limitation of the study is the use of pine trees as the sole vegetative indicator of response to fertilization. Understandably, pine growth is of paramount interest to the industrial forest manager. Yet the response of non-pine vegetation, ranging from hardwood trees and shrubs to herbaceous plants, is important for several reasons. First, this vegetation is potentially competitive with pine for available resources. Theoretically, large increases in non-pine biomass due to fertilization may at some point negatively influence pine growth. Second, the quality and quantity of non-pine vegetation are important determinants of wildlife habitat. For example, different fertilization regimes may create uniquely different sets of understory and ground cover structural characteristics. Finally, non-pine vegetation is the chief source of plant diversity in plantations. Such vegetation is important for enhancing stand-level biodiversity within intensively managed pine forests.

This study describes the 2-year responses of pines and non-pine vegetation to different fertilization rates at three RW 18 sites in Arkansas, Mississippi, and Louisiana. Although RW 18 was designed as a rate and frequency experiment, the sites we selected were not fertilized a second time until after our study was completed. Therefore, we did not examine the effects of varying fertilization frequencies on plant growth.

METHODS

Study Sites

The three NCSFNC RW 18 field sites chosen for this study were 4- to 6-year-old loblolly pine plantations in the Upper Coastal Plain. The sites were located: (1) south of Warren, AR on land owned by Potlatch Corporation; (2) north of Meridian, MS on land owned by Plum Creek; and (3) north of Leesville, LA on land owned by Boise. All sites were fertilized by hand in the winter of 1999-2000. Each installation had two replications of five treatments: 0 kg per ha N and 0 kg per ha P, 67 kg per ha N and 7 kg per ha P, 134 kg per ha N and 13 kg per ha P, 202 kg per ha N and 20 kg per ha P, and 269 kg per ha N and 27 kg per ha P. Each study site contained 10 plots that averaged 0.04 ha in size. The plots at each site were blocked to minimize pretreatment variation in volume, basal area, total height, and density of the planted pines. An analysis of variance indicated no significant pretreatment differences (α = 0.05) in these parameters at any site.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Table 1—Pre-treatment characteristics at the three study sites

	Arkansas	Mississippi	Louisiana
Pine age (*years*)	4	4	6
Pine density (*trees per ha*)	1,255	1,630	1,775
Mean pine d.b.h. (*cm*)	5.8	5.1	7.6
Mean pine height (*m*)	3.8	4.0	5.9
Mean pine basal area (m^2 *per ha*)	3.0	5.7	8.3
Soil series	Stough	Smithdale	Sacul
Soil texture	Fine sandy loam	Fine sandy loam	Sandy loam

Pine Measurements

Pine trees were measured at each study area during the winter of 1999-2000 (pretreatment), 2000-2001 (after 1 growing season), and 2001-2002 (after 2 growing seasons). Measurements included d.b.h. and total height; heights were measured with a height pole or hypsometer. In September 2001, pine leaf area index (LAI) in each plot was measured with a LI-COR LAI-2000 canopy analyzer (LI-COR Incorporated, Lincoln, Nebraska). LAI measurements were taken during the first and second week of September, which is the period of maximum LAI for loblolly pine in the South (Sampson and Allen 1999).

Non-Pine Biomass Measurements

In August 2001 (i.e., near the end of the second growing season after fertilization), two 1-m^2 biomass plots were systematically established in each treatment plot to sample non-pine vegetation. With 2 replicates per treatment, there were a total of 20 biomass plots per study site. All living vegetation rooted within each 1-m^2 plot was hand clipped at ground level. Plants were categorized by one of three vegetation types: grasses, sedges, and rushes; forbs; or woody stems. Samples were taken to a laboratory at the University of Arkansas-Monticello and oven dried at 60 °C for 48 hours. After the samples dried, they were weighed to determine oven-dry biomass.

Data Analysis

For pine d.b.h., pine total height, pine LAI, and non-pine biomass 2 years after fertilization, a complete randomized design (CRD) was used to test for differences among the treatments at each site using $\alpha = 0.05$. Data were analyzed with the general linear model (PROC GLM) of the Statistical Analysis System (SAS Institute Inc. 1989). Tukey's multiple range test (α=0.05) identified statistical groupings when a significant difference was detected through the GLM procedures.

RESULTS AND DISCUSSION

The pre-treatment characteristics of each study area are listed in table 1. The Louisiana stand was the oldest (6 years) and had the greatest pine density, the largest mean pine d.b.h. and height, and the highest pine basal area. The Arkansas and Mississippi sites were the same age (4 years); the Arkansas site had the lowest pine stem density, mean pine height, and pine basal area.

Two years after fertilization, pine d.b.h. at all three sites generally increased with increasing fertilization rates (table 2). Significant differences were observed in the Arkansas and Mississippi plantations. In Arkansas, mean 2-year d.b.h. growth ranged from 4.9 cm in the untreated control to 6.1 cm in the 269 kg per ha N treatment. In Mississippi, mean d.b.h. growth varied from 4.4 to 5.6 cm. Mean diameter growth was lowest at the Louisiana site and ranged from 2.8 to 3.2 cm after 2 years. These results are consistent with those from other RW 18 installations in the

Table 2—Mean d.b.h. growth, height growth, and leaf area index 2 years after fertilization for loblolly pine trees at the three study sites[a]

Treatment	D.b.h. growth	Height growth	LAI
kg N per ha	*cm*	*m*	
	Arkansas		
0	4.9a	2.1a	2.1a
67	5.3ab	2.1a	2.0a
134	5.6ab	1.9a	2.2a
202	5.9b	1.9a	2.5a
269	6.1b	1.8a	2.2a
	Mississippi		
0	4.4a	2.7a	2.2a
67	4.9ab	2.7a	2.1a
134	5.4ab	2.8a	2.2a
202	5.4ab	2.7a	2.3a
269	5.6b	2.7a	2.6b
	Louisiana		
0	2.8a	2.0a	2.2a
67	2.8a	2.1a	2.3a
134	3.0a	2.0a	2.6b
202	3.0a	2.0a	2.7bc
269	3.2a	2.0a	2.9c

LAI = leaf area index.

[a] For a given site, column means followed by the same letter are not significantly different at $\alpha = 0.05$.

Southern United States. Of the 13 sites not examined in our study, 11 showed significant positive d.b.h. growth responses 2 years after fertilization (NCSFNC 2002b). In addition, Haines and Haines (1979) reported a significant increase in pine d.b.h. growth 2 years after fertilizing a 4-year-old loblolly pine plantation in North Carolina.

Two-year pine height growth response to fertilization was variable and did not significantly differ by treatment at the study areas (table 2). In Arkansas, a severe ice storm in December 2000 damaged the crowns of many pines, particularly those that received higher rates of fertilization. In fact, 2-year height growth was lowest (1.8 m) in the 269 kg per ha N treatment and highest (2.1 m) in the control and 67 kg per ha N plots. In Mississippi, mean height growth ranged from 2.7 to 2.8 m. Similar to d.b.h. growth, mean height response was lowest at the Louisiana stand and varied from 2.0 to 2.1 m. That pine height growth was less sensitive to fertilization than d.b.h. appeared to be a regional phenomenon. Among the RW 18 stands, only 6 of the other 13 sites reported significant height growth responses 2 years after fertilization (NCSFNC 2002b).

There were no significant differences in pine LAI by treatment in Arkansas 2 years after fertilization (table 2). At this site, LAI ranged from 2.0 to 2.5. In Mississippi, the 269 kg per ha N plots had a significantly higher LAI (2.6) than the other treatments, in which LAI ranged from 2.1 to 2.3. Only at the Louisiana plantation was there a pattern of significantly higher LAI with increasing fertilization rate. LAI ranged from 2.2 in the control to 2.9 in the 269 kg per ha N treatment.

There were no significant differences by treatment for grass biomass, forb biomass, and total biomass at any of the sites (table 3). Woody biomass was significantly greater in the 269 kg per ha N plots in Arkansas and Mississippi, but not in Louisiana. Total biomass values for all treatments in Louisiana were far below those at the other sites, primarily because of a sparse woody understory component. The overall muted understory biomass response to fertilization contrasts with a number of other studies in loblolly pine plantations. For example, Brockway and others (1998) and Wolters and others (1995) reported significant increases in herbaceous plant production for the first 3 years after time of planting fertilization in sites throughout the West Gulf Coastal Plain. In Louisiana, Tiarks and Haywood (1986) found that significant increases in herbaceous biomass were maintained for 4 years after time of planting fertilization. Also in Louisiana, Haywood and Thill (1995) observed significant increases in herbaceous production 1 and 2 years after time of planting fertilization. In North Carolina, Haines and Haines (1979) reported a 30 percent increase in ground cover biomass 2 years after fertilizing a 4-year-old plantation. Such increases in understory plant biomass appear to be short-term gains that are generally not maintained for longer than 5 years (Brockway and others 1998, Tiarks and Haywood 1986, White 1977, Wolters and

Table 3—Mean non-pine biomass (g per m^2) by treatment 2 years after fertilization at the three study sites[a]

Treatment	Grasses,sedges and rushes	Forbs	Woody stems	Total
(*kg N per ha*)				
		Arkansas		
0	30.0a	15.0a	49.8ab	94.8a
67	26.4a	23.0a	18.1a	67.5a
134	18.6a	6.0a	120.2ab	144.7a
202	46.4a	9.6a	78.2ab	134.2a
269	11.1a	16.0a	124.6b	151.7a
		Mississippi		
0	24.7a	7.4a	159.6a	191.7a
67	39.1a	17.9a	209.2ab	266.2a
134	22.8a	47.9a	162.7ab	233.4a
202	38.1a	14.1a	114.7a	166.9a
269	12.8a	33.1a	278.1b	324.0a
		Louisiana		
0	39.7a	1.0a	28.5a	69.2a
67	25.7a	4.5a	10.0a	40.2a
134	51.4a	1.0a	9.1a	61.5a
202	42.9a	1.3a	17.3a	61.5a
269	11.4a	1.7a	14.2a	27.2a

[a] For a given site, column means followed by the same letter are not significantly different at $\alpha = 0.05$.

Schmidtling 1975, Wolters and others 1995), probably because closure of the pine canopy reduces understory production.

CONCLUSIONS

The response of pines and non-pine vegetation in this study was less than we anticipated. Overall, there was not a consistent pattern of significantly increased growth with increasing fertilizer rate. The limited number of differences between treatments may be explained by a number of potential factors. First, climatic events probably negatively affected plant growth during part of the study period. For example, drought conditions existed at all three study areas in 1999 and 2000; growing season precipitation during these years was far below normal (Agricultural Weather Information Services, Auburn, AL). In addition, the December 2000 ice storm broke the tops of many pine trees at the Arkansas site. Second, this study examined short-term (2 years) responses to fertilization. Perhaps this was too limited a time period for biological patterns to emerge, particularly for pine trees. Third, our biomass sampling intensity may not have been adequate. We established only two 1-m^2 biomass plots in each treatment plot at each site. Field observations at the Arkansas and Mississippi sites 2 years after fertilization indicated greater understory biomass in the more heavily fertilized plots. That these differences were not detected in our data suggest that greater sampling intensity may have been warranted. Finally, pine d.b.h. and non-pine biomass response to fertilization in Louisiana were probably influenced by the pine canopy. The Louisiana plantation was 2 years older than the stands in Arkansas and Mississippi and, in contrast with these sites, had a distinctly closed canopy. The resulting overstory competition and shaded conditions likely inhibited pine d.b.h. growth and the development of a productive understory community regardless of fertilization treatment.

Because of any or all of the aforementioned reasons, results from this study remain inconclusive. Continued measurements from the treatment plots are needed to describe more clearly the effects of fertilization on pines and non-pine vegetation in young loblolly pine plantations. Long-term results from RW 18 sites throughout the South will help determine whether fertilizing young pine stands, like midrotation fertilization, becomes an operational silvicultural practice.

ACKNOWLEDGMENTS

Technical and/or financial support for this project was provided by Potlatch Corporation, Plum Creek, Boise, and the North Carolina State Forest Nutrition Cooperative.

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WITHIN AND BETWEEN CANOPY VARIABILITY OF FOLIAR NITROGEN CONCENTRATION FOR LOBLOLLY AND SLASH PINE STANDS PLANTED AT DIFFERENT DENSITIES

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Abstract—Mid-summer foliar nitrogen concentrations (N) were measured at three canopy positions (upper, middle, lower), two foliage ages per canopy position (current-year and 1-year-old), and two flushes per age class (first flush and second flush) in 4-year-old loblolly (*Pinus taeda* L.) and slash pine (*Pinus elliottii* Engelm.) stands planted at 740, 2,220, and 3,700 trees ha^{-1} to (1) determine differences in foliar N due to species and planting density, (2) quantify variability within canopies, and (3) determine what factors are important to consider when making comparisons between stands with different canopy structures. Overall, foliar N was greater for loblolly pine than slash pine (11.9 vs. 10.1 mg g^{-1}) and decreased with stand density (12.2, 10.7, and 10.1 mg g^{-1} for stands with 740, 2,220, and 3,700 trees ha^{-1} respectively). Foliar N of current-year foliage (11.9 mg g^{-1}) was greater than 1-year-old foliage (10.2 mg g^{-1}). Several interactions occurred between factors of interest due to changes in the magnitude of differences, not due to changes in the direction of response.

INTRODUCTION

Foliar nitrogen concentration (N) of southern pine stands is influenced by N availability (e.g., Munger and others, in press; Murthy and others 1996; Will and others 2001; Zhang and Allen 1996). N availability is a function of supply (modified by site quality or fertilization) and uptake by the stand (modified by stand density or growth rate). Monitoring foliar N is useful to determine potential deficiencies and possibly to predict growth rate (McNeil and others 1988, Valentine and Allen 1990). However, measuring foliar N is complicated by variability within canopies, e.g., canopy position, foliage age, and flush. Standard procedure is to measure recently developed, sunlit foliage from the upper canopy during mid-winter. However, this ignores variability within the canopy and ignores foliar N status during the growing season when N is in greatest demand. As a result, impacts of treatments such as spacing and fertilization on foliar N might not be measured if they are transitory or occur only in certain canopy positions.

Our objectives were to (1) determine differences in growing season foliar N for intensively managed loblolly (*Pinus taeda* L.) and slash pine (*Pinus elliottii* Engelm.) stands planted at different densities, (2) quantify variability in foliar N within canopies, and (3) determine what factors are important to consider when making comparisons between stands with different canopy structures.

METHODS

An experiment using the factorial combination of species (loblolly pine and slash pine) and stand density (740, 2,220, and 3,700 trees ha^{-1}) was planted in January 1996 at three sites (blocks) on the lower Coastal Plain of south Georgia. Slash pine stands were planted with half-sib family 5-61 (JSC/CCA and Champion Paper) and loblolly pine stands were planted with half-sib family 7-56 (North Carolina State Tree Improvement Cooperative). Stands were kept free of competing vegetation. Stands received 56.1 kg ha^{-1} each of elemental N, P, and K in the spring of 1996. In the spring of 1998, stands received 67.3 kg ha^{-1} each of elemental N, P, and K as well as an additional 45 kg ha^{-1} of elemental N. Other macronutrients and a suite of micronutrients were also applied at this time to prevent deficiencies (14 kg Mg ha^{-1}, 27 kg Ca ha^{-1}, 80 kg S ha^{-1}, 0.5 kg B ha^{-1}, 1.4 kg Fe ha^{-1}, 1.7 kg Mn ha^{-1}, 1.7 kg Zn ha^{-1}, and 0.7 kg Cu ha^{-1}). An additional 45 kg ha^{-1} of elemental N was applied in the spring of 1999.

During August of 1999 (fourth growing season), composite foliar samples (10-20 fascicles each) were collected from 10 trees per plot. Separate samples were taken from three canopy positions (upper, middle, and lower), two foliage age classes (1-year-old foliage and current-year foliage), and two flushes per age class (first flush and second flush). Samples were dried at 60 °C and ground. N was determined using an NC2100 CNS analyzer and an NA1500 C/H/N analyzer (CE Elantech Inc., Lakewood, NJ, USA). Data were analyzed using a split-split-split plot analysis to determine the effects of species, stand density, canopy position, age class, and flush as well as all interactions.

RESULTS

Overall, a large amount of variability occurred within the canopies (figs. 1 and 2). Foliar N was consistently greater in loblolly than slash pine, greater in the 740 trees ha^{-1} stands compared to the 2,220 and 3,700 trees ha^{-1} stands, and greater in the current-year than 1-year-old foliage. Several interactions occurred (table 1) that were due to changes in the magnitude of differences, not due to changes in the direction of response. Specifics are listed.

1. Foliar N of loblolly pine (11.9 mg g^{-1}) was greater than slash pine (10.1 mg g^{-1}), but the magnitude depended on foliage year, spacing, and flush (significant species*year, species*spacing*year, species*flush, and species*flush*year interactions).

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

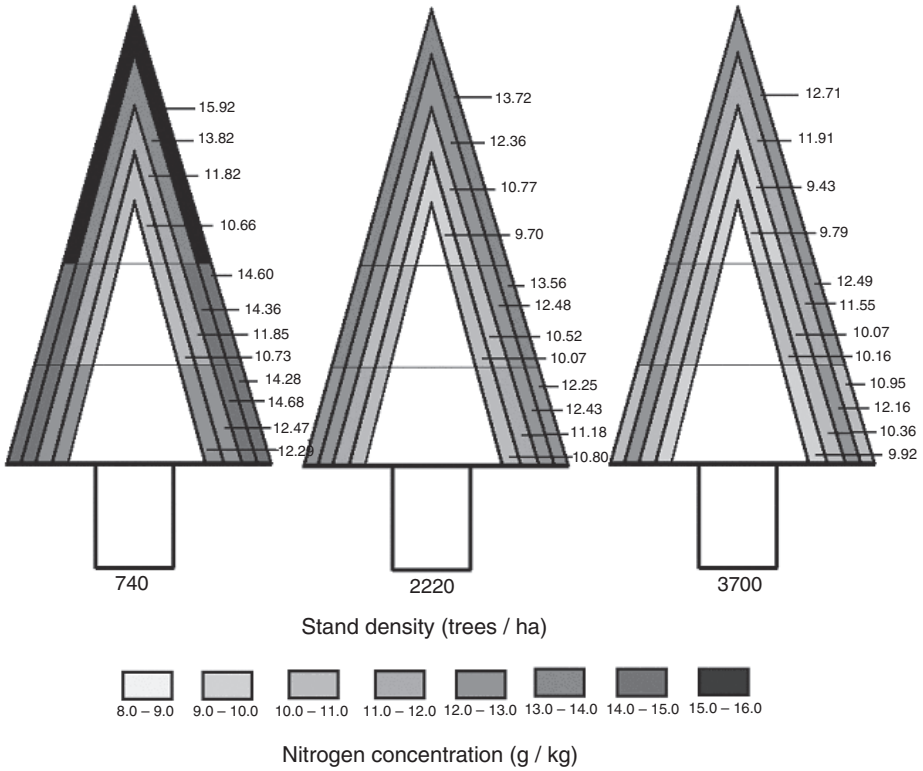

Figure 1—Loblolly pine foliar nitrogen concentrations during the fourth growing season for trees planted at different densities. Foliage was sampled from three canopy positions (upper, middle, lower), two age classes (1-year-old, current-year), and two flushes (first, second). Data are presented in g kg^{-1}.

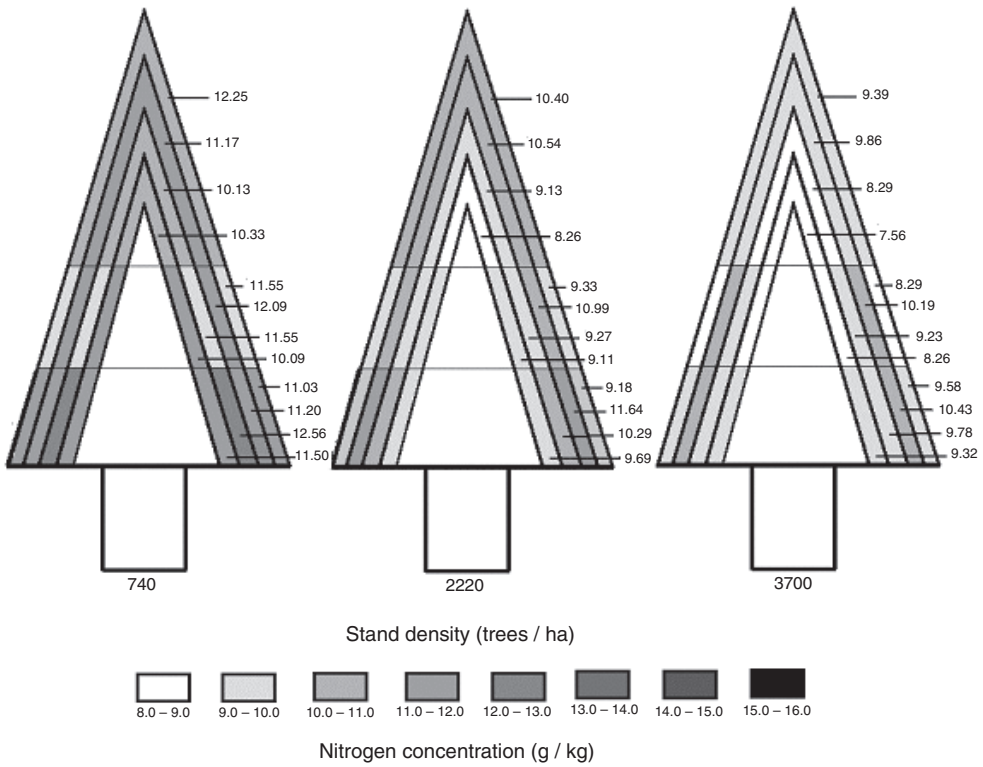

Figure 2—Slash pine foliar nitrogen concentrations during the fourth growing season for trees planted at different densities. Foliage was sampled from three canopy positions (upper, middle, lower), two age classes (1-year-old, current-year), and two flushes (first, second). Data are presented in g kg^{-1}.

Table 1—P values from split-split-split plot analysis

Source	df	p value
Site	2	
Species	1	> 0.0001
Spacing	2	> 0.0001
Spec*Spac	2	0.96
Error1	10	
Position	2	0.22
Spec*Pos	2	0.12
Spac*Pos	4	0.83
Spec*Spac*Pos	4	0.47
Error2	24	
Year	1	> 0.0001
Pos*Year	2	> 0.0001
Spec*Year	1	> 0.0001
Spac*Year	2	0.11
Spac*Pos*Year	4	0.78
Spec*Pos*Year	2	0.67
Spec*Spac*Year	2	0.01
Spec*Spac*Pos*Year	4	0.53
Error3	36	
Flush	1	0.11
Flush*Year	1	> 0.0001
Pos*Flush	2	0.0002
Spec*Flush	1	0.009
Spac*Flush	2	0.002
Pos*Flush*Year	2	> 0.0001
Spec*Flush*Year	1	0.001
Spac*Flush*Year	2	0.19
Spac*Pos*Flush*Year	4	0.15
Spec*Spac*Flush*Year	2	0.08
Spec*Pos*Flush*Year	2	0.22
Spec*Pos*Flush	2	0.14
Spac*Pos*Flush	4	0.74
Spec*Spac*Pos*Flush	4	0.28
Spec*Spac*Flush	2	0.05
Spec*Spac*Pos*Flush*Year	4	0.15
Error4	69	

Species are loblolly and slash pine, spacings are 740, 2,220, and 3,700 trees ha^{-1}, positions are upper, middle, and lower canopy, years are current-year and 1-year-old foliage, and flushes are first and second flush. Significant interactions that occurred were due to changes in the magnitude of differences, not due to changes in treatment rank.

2. Foliar N was greater for the 740 trees ha^{-1} stands (12.2 mg g^{-1}) than for the 2,220 (10.7 mg g^{-1}) or 3,700 (10.1 mg g^{-1}) trees ha^{-1} stands, but the magnitude depended on species, spacing, year, and flush (significant spacing*flush and species*spacing*year interactions).
3. Foliar N of current-year foliage (11.9 mg g^{-1}) was greater than 1-year-old foliage (10.2 mg g^{-1}), but the difference depended on spacing, species, canopy position, and flush (significant position*year, species*year, species*spacing*year, flush*year, and position*year*flush interactions).

DISCUSSION

Clear differences in foliar N were associated with species, stand density, and foliage age. As expected from previous studies, foliar N was lower for slash pine than for loblolly pine (Samuelson 2000, Will and others 2001) and higher in younger foliage (e.g., Munger and others, in press; Will and others 2001; Zhang and Allen 1996).

The decline in foliar N with increasing stand density occurred even though the stands had been fertilized with more than 210 kg ha^{-1} of elemental N. This indicates that the extremely rapid growth rates of the high density stands were exceeding the ability of the soil and supplemental fertilizer to meet the demand for N. Stem growth of the denser stands was becoming limited (Barron-Gafford and others 2003, Burkes and others 2003) and lower foliar N in the dense stands may have been a contributing factor (Barron-Gafford and others 2003). Foliar critical concentration for N is considered to be 12.0 mg g^{-1} in loblolly pine (Jokela and others 1991) and 10.0 mg g^{-1} in slash pine (Fisher and Binkley 2000). For both species, mid-summer estimates of average upper canopy foliar N dipped below critical concentration as stand density increased from 740 to 3,700 trees ha^{-1} (from 13.0 to 10.9 mg g^{-1} for loblolly pine and from 10.9 to 8.8 mg g^{-1} for slash pine). Foliar critical concentrations are based on dormant season measurements and would likely be greater than mid-summer concentrations. However, an adjustment for sampling season would probably not be enough to raise foliar concentrations of the densely planted stands above critical concentrations (Murthy and others 1996, Zhang and Allen 1996).

Unlike other studies that found foliar N to decrease with increasing canopy height (Wells and Metz 1963, White 1954), the main effect of canopy position was not significant in this study. However, canopy position was involved in several interactions such that it decreased with canopy height for the older foliage.

Within a given canopy, the difference in foliar N was as large as 5.3 mg g^{-1}, indicating sampling location had a large impact and that inconsistency in sampling location would mask treatment effects. However, given the general consistency of species and stand density effects within a particular canopy section, the treatment effects on foliar N would have been detected as long as samples were chosen from the same section. This result is particularly robust since stand structure in this experiment was very different between treatments.

ACKNOWLEDGMENTS

We thank the Georgia Traditional Industries Program in Pulp & Paper for funding and the Plantation Management Research Cooperative and their industrial cooperators for funding and support.

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Pine Planting, Stocking, Spacing

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GENETIC AND SPACING EFFECTS ON LOBLOLLY PINE PLANTATION DEVELOPMENT THROUGH AGE 17

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Abstract—Eight North Carolina families and a Mississippi-Alabama commercial check of loblolly pine (*Pinus taeda* L.) were planted at three spacings (5x5, 8x8, and 10x10 feet) in east Mississippi. Results for ages 5, 9, 13, and 17 years indicated that spacing effects occurred by age 5 for d.b.h. and height and by age 9 for survival, stand volume, and periodic annual increment (PAI) in volume. D.b.h. decreased as spacing decreased. Height was temporarily stimulated as trees began to compete with each other. Density-related mortality began between ages 5 and 9 for the 5x5 and between ages 9 and 13 for the 8x8 and 10x10. Peak PAI occurred during these same periods. The 5x5 spacing had the greatest stand volume at ages 9 and 13, but by age 17, the 8x8 and 5x5 spacings were similar. Family effects were detected by age 5 for d.b.h., height, stand volume, and PAI. Survival differences among families became significant by age 13. Family NC1 consistently ranked highest in stand volume at all ages, and it had 27 percent more volume per acre than the local check at age 17. The primary contributor to family differences for stand volume was survival. Family-by-spacing interactions were seldom significant.

INTRODUCTION

Selections of a spacing and genetic source of seedlings are two of the most important decisions that must be made during establishment of forest plantations. These decisions will predetermine future timing of silvicultural treatments, productivity of the plantation, and quality of harvested wood.

Numerous spacing studies with loblolly pine (*Pinus taeda* L.) have been established to evaluate and model density effects on growth (Smith and Strub 1991). Unfortunately, most of the studies do not have a family component to examine genetic effects. Also, many of the reports have been for measurements taken at young ages. A recent paper by Sharma and others (2002) provides information for measurements taken through age 16 for spacings ranging from 4x4 feet to 12x12 feet. However, the study used only one source of genetic material. A paper by Matyas and Varga (2000) provided 25-year data for spacing trials of Scots pine (*Pinus sylvestris* L.) established with grafted clones. Those authors showed that spacing affected early phases of stand development and allocation rates to different parts of the tree. Genetic effects could not be traced, however, because of large within-clone variation and a small number of replications.

The present study was designed to investigate how initial spacing and family "types" affect loblolly pine stand development. Such an investigation requires large, adequately replicated plots containing families of predetermined growth types that are grown under various spacings without thinning and measured through the periods of crown closure and self thinning. Results to age 5 (prior to crown closure) were reported by Land and others (1991) at the Sixth Biennial Southern Silvicultural Research Conference. This paper examines stand development from age 5 to age 17.

METHODS

Eight open-pollinated families from North Carolina that were pre-selected for differences in growth rate and crown size (from earlier progeny tests in North Carolina) (Land and others 1991) were planted at three spacings in east-central Mississippi and compared with a local unselected check for stand development through age 17. Spacings were 5x5 feet, 8x8 feet, and 10x10 feet. Families NC1 and NC8 had the type "fast growth and small crown", families NC4 and NC7 were typed as "fast growth and large crown", families NC3 and NC6 were "slow growth and small crown" types, and families NC2 and NC5 were classified as "slow growth and large crown" types. The check was a mixture of seeds from trees in Lowndes and Kemper Counties of east-central Mississippi and Fayette and Pickens Counties in west-central Alabama. Containerized seedlings of the nine genetic sources were provided by Weyerhaeuser Company.

The study was established in early 1985 as a randomized complete block design with treatments arranged in split-split plots and repeated on two adjacent sites: one an old field and the other a cutover-and-site-prepared area. There were four replications on each of the two sites. Each replication was split into three spacing plots of equal acreage. Each spacing plot was split into a "mixture" subplot and a "single-family" subplot of genetic deployments. However, the mixture subplots were not included in the analyses and results for this paper. Therefore, the analyses reported here used a split-plot design with nine single-family subplots within each spacing main plot of each replication. Each single-family subplot had a single or double border row around an interior set of measurement trees that covered the same acreage (40 feet x 40 feet, or 0.0367 acres) in all spacings. Thus, a single-family subplot contained 16 measurement trees at 10x10-foot spacing, 25 measurement trees at 8x8-foot spacing, and 64 measurement trees at 5x5-foot spacing.

Survival, d.b.h., and height were measured at ages 5, 9, 13, and 17 years. Stem volume in total cubic feet outside bark was estimated for each tree by the following equation provided by Dr. Tom Matney at Mississippi State University for old-field loblolly pine:

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Volume = 0.00250 x d.b.h.^{2} x ht. (1)

Single-family subplot values for survival, d.b.h., height, and stand volume per acre were calculated for each of the 4 years. Dominant height (co-dominant and dominant trees only) was also calculated at ages 9, 13, and 17 years. Eighteen of the 216 subplots had to be discarded at age 17 because bark-beetle-caused mortality was greater than 20 percent in those plots. Periodic annual increment (PAI) in stand volume was calculated for each subplot for the four periods, 0-5 years, 5-9 years, 9-13 years, and 13-17 years. Subplot values were used in analyses of variance based on a mixed-effects model, where spacings and families were treated as fixed effects and replications and planting sites were considered random effects. A full analysis with all sources of variation was conducted first for each trait at each age. If higher-order interactions were not significant, they were pooled with the error term for a final analysis. The Tukey-Kramer procedure was used for all pairwise comparisons among spacing means and among family means (SAS Institute Inc. 1999).

RESULTS AND DISCUSSION

Spacing Effects

Spacing effects on survival—Differences among spacings in survival were not significant at age 5, but they had become significant by age 9 (table 1). The 5x5 spacing was significantly lower in survival than the wider two spacings at age 9, and by ages 13 and 17 all three spacings were significantly different from each other (table 2). Crown closure and self thinning started between ages 5 and 9 in the 5x5 spacing and between ages 9 and 13 in the 8x8 and 10x10 spacings. There was a decline of 1 percent per year in survival before age 5, 2 percent per year during the period of crown closure and initiation of self thinning, and 2.5 percent to 4.5 percent per year in the 4-year periods after the initiation of self thinning. As a result, the 5x5 spacing had 53 percent survival at age 17, the 8x8 had 70 percent, and the 10x10 had 74 percent (reflecting differences in the length of time since initiation of self thinning).

Spacing effects on stem diameter—Close spacings resulted in smaller d.b.h. than wide spacings at the same age. These spacing effects were already significant at age 5 (table 1), before the onset of self thinning. The early difference was due to the 5x5 spacing, which had a significantly smaller d.b.h. than the two wider spacings at age 5 (table 3). By age 9 and thereafter, all three spacings were significantly different from each other. At age 17 the mean tree d.b.h. in the 5x5 spacing was 5.9 inches, while the 8x8 and 10x10 spacings had d.b.h.s of 8.0 and 9.3 inches, respectively.

Spacing effects on tree height—Mean height (all trees) differed significantly among spacings at all 4 ages (table 1), but the spacing with the tallest trees differed for the different ages (table 4). Height growth was temporarily stimulated at the time of crown closure. Trees were tallest in the 5x5 spacing at age 5, equally tall in the 5x5 and 8x8 spacings at age 9, tallest in the 8x8 at age 13, and equally tall in the 8x8 and 10x10 spacings at age 17. The difference between the tallest and shortest spacings for mean heights at a given age increased from approximately 1.5 feet at ages 5 and 9 to 4.5 feet at age 17. All living trees were included in the means, so part of the decline in rank of the closer spacings at the older ages could be due to the inclusion of the intermediate and overtopped crown classes. This possibility was supported by analyses of dominant heights (co-dominant and dominant trees only). Those analyses showed the same trends as seen in table 4, except that the spacing means were 1.0 to 1.5 feet taller than for all trees, and the difference between the tallest and shortest means was reduced to 3.5 feet at age 17. The rankings and significance of differences among spacing means remained the same for dominant height as for height of all trees. Thus, part of the temporary stimulation effect on height is a “real” effect (rather than a confounded effect from inclusion of intermediate and overtopped trees). By age 17 and thereafter, however, the shortest trees will be in the 5x5 spacing, and the tallest trees will be in the 10x10 spacing.

Table 1—F-test significance of sources of variation for five traits across four ages in a 17-year-old loblolly pine spacing and genetics trial

Source of variation	d.f.	Survival age =				DBH age =				Height age =				Stand volume age =				Volume PAI age =			
		5	9	13	17	5	9	13	17	5	9	13	17	5	9	13	17	5	9	13	17
Locs [=L]	1	ns	ns	ns	ns	**	**	ns	ns	**	**	ns	**	**	**	ns	ns	**	*	ns	ns
Reps/L[R(L)]	6	**	**	**	**	**	ns	**	*	**	*	*	*	**	*	**	ns	**	**	**	**
Spacings[=S]	2	ns	**	**	**	**	**	**	**	**	*	**	**	ns	**	**	**	ns	**	**	**
S x L	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	**	ns	ns	ns	**	ns	ns	ns
S x R(L)	12	*	ns	ns	ns	ns	**	*	*	*	**	**	**	**	ns	ns	ns	**	ns	ns	ns
Families[=F]	8	ns	ns	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**
F x L	8	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
F x R(L)	48	*	ns	*	ns	ns	ns	*	**	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns
F x S	16	*	ns	ns	*	ns	ns	ns	**	ns	ns	ns	ns	*	ns	ns	ns	*	ns	**	ns
Pooled error	112[a]																				

PAI = periodic annual increment; ns = non-significant; * = significant at 0.05 probability; ** = significant at 0.01 probability.
[a] Or 94 at age 17.

Table 2—Spacing and family effects on survival at four ages in a 17-year-old loblolly pine study

Effects	Survival at four ages (years)			
	5	9	13	17
	percent			
Study mean	94.5	87.7	77.4	66.4
Spacing:				
5x5 feet	94 A	85 b	71 C	53 c
8x8 feet	95 A	88 a	79 B	70 b
10x10 feet	94 A	90 a	82 A	74 a
Family:				
Local check	95 a	88 A	76 bc	61 CD
NC fast growth & small crown:				
NC1	95 a	92 A	88 a	78 A
NC8	92 a	84 A	73 c	61 CD
NC fast growth & large crown:				
NC4	96 a	91 A	82 ab	68 BCD
NC7	95 a	88 A	78 bc	68 BC
NC slow growth & mall crown:				
NC3	95 a	84 A	71 c	60 D
NC6	95 a	87 A	76 bc	63 BCD
NC slow growth & large crown:				
NC2	94 a	87 A	75 bc	64 BCD
NC5	94 a	88 A	77 bc	70 AB

Means followed by the same letter (and case) within a column are not significantly different at the 0.05 level. The family mean with a single underline is the largest mean at that age, and the family mean with a double underline is the smallest mean at that age.

Table 3—Spacing and family effects on mean diameter (d.b.h.) at four ages in a 17-year-old loblolly pine study

Effects	D.b.h. at four ages (years)			
	5	9	13	17
	inches			
Study mean	2.47	5.29	6.86	7.82
Spacing:				
5x5 feet	2.37 B	4.23 c	5.21 C	5.92 c
8x8 feet	2.50 A	5.53 b	7.16 B	8.03 b
10x10 feet	2.54 A	6.11 a	8.22 A	9.34 a
Family:				
Local check	2.41 c	5.30 AB	6.89 ab	7.92 AB
NC fast growth & small crown:				
NC1	2.64 a	5.36 AB	6.77 b	7.63 B
NC8	2.44 bc	5.34 AB	7.09 a	8.02 A
NC fast growth & large crown:				
NC4	2.61 ab	5.43 A	6.88 ab	7.74 AB
NC7	2.45 abc	5.33 AB	6.97 ab	7.77 AB
NC slow growth & small crown:				
NC3	2.46 ab	5.31 AB	6.88 ab	7.81 AB
NC6	2.51 ab	5.26 ABC	6.71 b	7.56 B
NC slow growth & large crown:				
NC2	2.45 abc	5.19 BC	6.87 ab	7.82 AB
NC5	2.26 c	5.10 C	6.72 b	7.60 B

Means followed by the same letter (and case) within a column are not significantly different at the 0.05 level. The family mean with a single underline is the largest mean at that age, and the family mean with a double underline is the smallest mean at that age.

Table 4—Spacing and family effects on mean height (all crown classes included) at four ages in a 17-year-old loblolly pine study

Effects	Four ages (years)			
	5	9	13	17
	height in feet			
Study Mean	15.0	33.1	50.3	60.5
Spacing:				
5x5 feet	15.9 A	33.5 a	48.6 C	57.4 b
8x8 feet	14.7 B	33.3 ab	52.0 A	61.8 a
10x10 feet	14.3 B	32.5 b	50.5 B	62.1 a
Family:				
Local Check	14.2 de	31.3 D	48.0 e	57.2 C
NC Fast Growth & Small Crown:				
NC1	16.1 a	34.6 A	51.4 a	61.7 A
NC8	15.0 cd	33.3 B	51.2 ab	61.9 A
NC Fast Growth & Large Crown:				
NC4	15.9 ab	34.6 A	51.7 a	61.0 A
NC7	15.0 cd	33.4 B	51.8 a	62.0 A
NC Slow Growth & Small Crown:				
NC3	14.8 cd	33.0 BC	50.1 bc	60.1 AB
NC6	14.8 cd	32.4 BCD	48.7 de	58.7 BC
NC Slow Growth & Large Crown:				
NC2	15.2 bc	33.4 B	50.6 abc	61.2 A
NC5	13.8 e	31.9 CD	49.8 cd	60.5 AB

Means followed by the same letter (and case) within a column are not significantly different at the 0.05 level. The family mean with a single underline is the largest mean at that age, and the family mean with a double underline is the smallest mean at that age.

Spacing effects on stand volume—Significant differences among spacings for stand volume were first detected at age 9 and remained significant through age 17 (table 1). However, the differences were greatest at ages 9 and 13 and had declined by age 17. At age 9, the 10x10 spacing had only half the volume of the 5x5, and the 8x8 was intermediate (table 5). By age 17, the 5x5 spacing had apparently reached carrying capacity for the site and the 8x8 had caught up, so that these two spacings were no longer different in stand volume. Volume for the 10x10 spacing was still significantly less than the other two, but it was closing on them and was 91 percent of the 5x5 volume. The reader is cautioned to remember that the same equation was used to calculate volumes in all spacings, so no accounting for differences in stem taper was provided. The spacing differences in actual volume may be larger than reported here.

Spacing effects and stand volume growth rate—Periodic annual increments (PAI) in stand volume differed significantly among spacings in the 5-to-9 age period, the 9-to-13 age period, and the 13-to-17 age period (table 1). However, the spacing with the greatest PAI differed for each of these periods (table 6). The 5x5 spacing had the greatest growth rate in cubic feet per acre per year during the 5-to-9 age period, the 8x8 had the greatest rate in the 9-to-13 age period, and the 10x10 had the greatest rate during the 13-to-17 age period. The peak (maximum) PAI occurred between ages 5 and 9 years for the 5x5 spacing and between ages 9 and 13 years for the 8x8 and 10x10 spacings. Based on the PAIs in the adjourning periods, the peak rate of growth probably occurred at ages 8-9 in the 5x5, ages 10-11 in the 8x8, and ages 12-13 in the 10x10. These peak values correspond with onset of self thinning in the different spacings.

Genetic Effects

Genetic effects on survival—Family differences in survival were first detected as significant at age 13 (table 1), which was when self thinning had begun in all spacings. Family NC1 (fast growth and small crown) had the highest survival at ages 13 and 17 (88 percent and 78 percent, respectively) (table 2). Family NC3 (slow growth and small crown) had the lowest survival at ages 13 and 17 (71 percent and 60 percent, respectively). The local check was among the lower ranking families for survival and was not significantly different from NC3. Since the families were competing only with themselves in the single-family subplots, the family differences must be due to differences in self-thinning rates rather than family differences in crown position and overtopping (as might occur in a mixture of families). This will be studied in subsequent analyses and is not included here.

Genetic effects on stem diameter—Family differences in mean tree d.b.h. were highly significant at age 5 and all ages thereafter (table 1). However, the rankings of the families changed radically between age 5 and age 17 (table 3), partly as a result of the family differences in survival that

Table 5—Spacing and family effects on stand volume (cubic feet per acre outside bark) at four ages in a 17-year-old loblolly pine study

Effects	Stand volume at four ages (years)			
	5	9	13	17
	cubic feet per acre			
Study Mean	237	1757	3729	4779
Spacing:				
5x5 feet	427 A	2390 a	4325 A	4953 a
8x8 feet	175 A	1619 b	3695 B	4883 a
10x10 feet	110 A	1262 c	3167 C	4509 b
Family:				
Local Check	216 cd	1669 BC	3516 d	4364 CD
NC Fast Growth & Small Crown:				
NC1	282 a	1933 A	4218 a	5550 A
NC8	234 bc	1792 AB	3835 bc	4861 BC
NC Fast Growth & Large Crown:				
NC4	270 ab	1954 A	4049 ab	4914 B
NC7	234 bc	1827 AB	3994 ab	5129 AB
NC Slow Growth & Small Crown:				
NC3	239 abc	1679 BC	3402 d	4335 CD
NC6	234 bc	1672 BC	3393 d	4246 D
NC Slow Growth & Large Crown:				
NC2	240 abc	1689 BC	3617 cd	4769 BCD
NC5	186 d	1597 C	3538 cd	4869 BC

Means followed by the same letter (and case) within a column are not significantly different at the 0.05 level. The family mean with a single underline is the largest mean at that age, and the family mean with a double underline is the smallest mean at that age.

Table 6—Spacing and family effects on periodic annual growth (PAI) in stand volume (cubic feet per acre per year) at four ages in a 17-year-old loblolly pine study

Effects	Periodic annual growth at four ages (years)			
	0–5	5–9	9–13	13–17
	cubic feet per acre per year			
Study Mean	47.5	379.9	493.0	260.7
Spacing:				
5x5 feet	85.5 A	490.6 a	483.9 B	150.2 c
8x8 feet	34.9 A	361.2 b	518.9 A	286.4 b
10x10 feet	22.0 A	287.9 c	476.2 B	332.4 a
Family:				
Local Check	43.2 cd	363.3 BC	461.7 cd	208.6 B
NC Fast Growth & Small Crown:				
NC1	56.4 a	412.7 A	571.2 a	329.4 A
NC8	46.9 bc	389.4 ABC	510.6 abc	242.3 AB
NC Fast Growth & Large Crown:				
NC4	54.0 ab	421.1 A	523.8 abc	218.0 B
NC7	46.8 bc	398.3 AB	541.7 ab	281.9 AB
NC Slow Growth & Small Crown:				
NC3	47.9 abc	360.0 C	430.6 d	233.2 B
NC6	46.7 bc	359.5 C	430.4 d	207.6 B
NC Slow Growth & Large Crown:				
NC2	48.0 abc	362.2 BC	482.1 bcd	282.2 AB
NC5	37.3 d	352.6 C	485.2 bcd	303.5 AB

Means followed by the same letter (and case) within a column are not significantly different at the 0.05 level. The family mean with a single underline is the largest mean at that age, and the family mean with a double underline is the smallest mean at that age.

caused density-related effects on diameter growth. An example was family NC1, which had the largest mean d.b.h. at age 5 (rank 1 of 9) and one of the smallest mean d.b.h. values at age 17 (rank 7 of 9). This family had the highest survival at age 17. Family NC8, which was the other fast-growth and small-crown family with NC1, exhibited the opposite change in rank. It was near the lower end of family means for d.b.h. at age 5 (rank 7 of 9) and at the top for family mean d.b.h. at age 17. It had the next-to-lowest survival at age 17. The local check acted much like NC8. It had the next-to-smallest mean d.b.h. at age 5 and next-to-largest mean d.b.h. at age 17. It was tied with NC8 for next-to-lowest survival at age 17.

Genetic effects on tree height—Differences among families in mean tree height (all trees) were highly significant at age 5 and all ages thereafter (table 1). Family ranks for height did not change as greatly between age 5 and age 17 as they did for d.b.h. (table 4). Dominant heights gave similar rankings and significance tests for family means, except that the dominant heights were taller than the mean heights by 1.0 feet at ages 9 and 13 and by 1.5 feet at age 17. Family NC1 had the tallest mean height at age 5 (16.1 feet) and was near the tallest at age 17 (61.7 feet = rank 3 of 9). The local check was next to the shortest in height at age 5 (14.2 feet), and it was the shortest of all families at age 17 (57.2 feet). Two families did increase in family rank from age 5 to age 17. Families NC7 and NC8 had middle ranks for height at age 5 (ranks 4 and 5 of 9), but they were tallest at age 17 (ranks 1 and 2, respectively). Both of these families were pre-selected for fast growth, but NC7 was classified as large crown and NC8 as small crown. Thus, 3 of the 4 "fast growth" families were the tallest 3 in rank at age 17. The pre-selections for fast growth (in height), based on 12-year performance in North Carolina progeny tests, were effective for performance through age 17 in Mississippi.

Genetic effects on stand volume—Family differences in stand volume were highly significant at all ages from 5 years through 17 years (table 1). Family NC1 consistently ranked highest in volume (rank 1 at ages 5, 13, and 17, and rank 2 at age 9) from the time of crown closure through the early stages of self thinning (table 5). By age 17 this family had 5,550 cubic feet per acre as compared with the check's value of 4,364 cubic feet per acre, or a realized gain of 27 percent. Family NC6 was in the lower half of the families for stand volume at age 5 (rank 6 of 9) and had the lowest volume of 4,246 cubic feet per acre at age 17 (3 percent below the check). Family ranks at age 5 were not always indicative of family performance at age 17 for stand volume, however. Family NC5 had the lowest stand volume at ages 5 and 9, but it had increased to rank 4 of 9 by age 17 and was not significantly different from the second-ranked family. The most important contributing factor to the family differences in stand volume was survival. Family NC1 ranked number 1 for survival and number 1 for stand volume at age 17, family NC6 ranked number 6 for survival and number 9 for volume, and the check ranked number 8 for survival and number 7 for volume. The families classified as "fast growth" in prior progeny tests (NC1, NC4, NC7, and NC8) generally had greater stand volumes at age 17 than those classified as "slow growth", but crown-size classification was only important in the "slow growth" class. The two families classified for slow growth and small crown size (NC3 and NC6) had the two lowest family values for 17-year stand volume.

Genetic effects on stand volume growth rate—Differences among families for periodic annual increments (PAI) in stand volume were highly significant for the 5 periods 0-5 years, 5-9 years, 9-13 years, and 13-17 years (table 1). Family rankings changed for some families from before age 9 to after age 9 (the onset of self thinning), and not for others (table 6). Family NC5 increased from the lowest growth rate before age 9 to the next to highest growth rate in the 13-17-year period. It is a slow starter but a good survivor. It was pre-selected for slow growth and large crown size. Family NC1 was an example of a family that did not change between the two periods. It consistently had the fastest or next-to-fastest growth rate before and after age 9. This family is a fast starter and a good survivor. It was pre-selected for fast growth and small crown size. The local check also did not change much from before age 9 to after age 9. It was next to lowest in stand growth rate for the 0-5 age period and for the 13-17 age period. It was a slow starter and a poor survivor.

Family-by-Spacing Interactions

Family-by-spacing interactions were usually not significant (table 1). Interactions for survival were detected at ages 5 and 17, but the differences were so small at age 5 that they had little practical meaning. By age 17 there were some minor changes in family ranks for survival among spacings, but the major contributor to the interaction was a greater spread in family means for the 8x8 and 10x10 spacings than for the 5x5 spacing. The only significant interaction found for stem diameter was at age 17, and this interaction was mainly due to a larger spread in family means at the wider spacings than at the 5x5 spacing. There were no family-by-spacing interactions for mean tree height at any age. The only age at which an interaction was detected for stand volume was age 5. This interaction was due to a wider spread in family means at the 5x5 spacing than at the other two spacings. Interactions were significant for PAI in stand volume during the first 5-year period and also during the period of onset of self thinning between ages 9 and 13 years. Both interactions were due to changes in spread of family means in the different spacings. For the first 5 years the greatest spread was in the 5x5 spacing, but for the 9- to 13-year period the greatest spread was in the 8x8 spacing. Family ranks changed little between spacings.

SUMMARY AND CONCLUSIONS

Spacing effects were seen on tree diameter and height before the onset of self thinning. Self thinning began around age 8-9 years in the 5x5 spacing, 10-11 years in the 8x8 spacing, and 12-13 years in the 10x10 spacing, as indicated by both the development of significant differences between spacings in survival and the timing of peak PAI values for annual growth in stand volume. Thus, differences among spacings in mean d.b.h. and height were already significant at age 5, but differences in survival and stand volume were not detected until age 9. D.b.h. was reduced by close spacing at age 5, and this difference between

spacings got larger with increasing age. However, mean tree height (all living trees included) was only temporarily stimulated by close spacing, so that the 5x5 spacing was tallest at age 5, the 8x8 was tallest at age 13, and the 10x10 was tallest at age 17. Part of the decline in mean height after crown closure may be from the inclusion of increased numbers of intermediate and overtopped trees in the height mean. The 5x5 spacing reached peak PAI for growth in stand volume around age 8-9 years and was approximately at carrying capacity for cumulative stand volume at age 17. The 8x8 spacing reached peak PAI around age 10-11 years and was approaching the same carrying capacity as the 5x5 spacing by age 17, so that these two spacings were no longer significantly different for stand volume at that age. The 10x10 spacing reached peak PAI around age 12-13 years, and the cumulative volume for this spacing at age 17 was 91 percent of the 5x5 value and closing on that value. By age 20, the three spacings might not differ in stand volume.

Genetic effects, averaged over spacings, were detected for all traits at all ages, with the exception of survival at ages 5 and 9. The ability to detect these effects was enhanced by the pre-selection of family "types" and the treatment of these families as fixed effects in the analyses of variance. "Fast-growth" families produced the most volume per acre at age 17, and "slow growth with small crown" families produced the least volume. The local check was next to lowest in volume per acre at age 17, indicating that selection in North Carolina progeny tests provided realized gains in plantings in Mississippi. The greatest contributor to family differences in stand development was survival. Family NC1 ranked at the top for survival and stand volume throughout the 17-year life of the stand, while NC6 ranked near the bottom (rank 6 of 9) for survival and had the lowest volume per acre at age 17. Family differences in survival caused differences in density-related stand characteristics and resulted in changes in family ranks for the periods before and after onset of self thinning. The family NC1 had the largest mean d.b.h. at age 5 and one of the smallest mean d.b.h. values at age 17, because the family's high survival caused a greater density effect than for other families with lower survival. Both rapid early growth and the ability to tolerate competition (maintain high survival after crown closure) are needed to maximize stand volume production. This combination occurs in family NC1.

Spacing-by-family interaction effects should not represent a major concern for tree improvement programs. Interactions were seldom detected, and most of those interactions were due to changes in spread between family means at the different spacings rather than changes in rank. However, information about the interactions might be used in decisions about spacings for progeny tests, so that the largest spreads among family means can be generated to increase selection efficiency. From an operational standpoint the changes in spread among families can be used to enhance yield by matching families with pre-determined spacings and rotation lengths.

ACKNOWLEDGMENTS

Approved for publication as Journal Article No. FO-224 of the Forest and Wildlife Research Center, Mississippi State University. We wish to thank Weyerhaeuser Company for providing and growing the containerized seedlings used for this study. Drs. Tom Terry and Clem Lambeth in Weyerhaeuser Company contributed both time and advice for design and establishment of the test. Finally, we gratefully acknowledge the guidance of Dr. George Switzer (deceased) from Mississippi State University in developing the study.

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STOCK TYPE AFFECTS PERFORMANCE OF SHORTLEAF PINE PLANTED IN THE OUACHITA MOUNTAINS THROUGH 10 YEARS

James P. Barnett and John C. Brissette[1]

Abstract—Shortleaf pine (*Pinus echinata* Mill.) seeds collected from several half-sib families were grown as both bare-root and container stock and outplanted on two sites in the Ouachita Mountains of Arkansas. When outplanted, the bare-root seedlings had greater mean height and root-collar diameter than the container seedlings. However, the container seedlings had greater mean root volume and more favorable shoot-to-root ratios than the bare-root stock. Survival of both stock types was excellent, exceeding 90 percent after 10 years. The container stock performed consistently better than the bare-root at each interval measured, but there were no statistically significant interactions between stock type and half-sib family at 3, 5, or 10 years.

INTRODUCTION

In the Ouachita and Ozark Mountains of Arkansas and Oklahoma, shortleaf pine (*Pinus echinata* Mill.) usually is planted on south- and west-facing slopes where soil moisture often is limited. One advantage of container-grown southern pine seedlings over bare-root planting stock is better performance on harsh, drought-prone sites (Barnett and Brissette 1986). Superior survival and growth of container seedlings on dry sites has been shown for longleaf pine (*P. palustris* Mill.) (Amidon and others 1982, Goodwin 1980) and for loblolly pine (*P. taeda* L.) (Goodwin 1980, South and Barnett 1986).

Shortleaf pine has not been compared in as many stock-type trials as the other southern pines. Ruehle and others (1981) compared container and bare-root shortleaf pine in an ectomycorrhizae study on two sites in the Ouachita Mountains. On the site with the best soil-moisture characteristics, the container seedlings survived better, grew taller, and had larger stem diameters than the bare-root stock. However, on the site with the drier moisture regime, container seedlings had poorer survival and growth. The authors concluded that the container seedlings, which were considerably smaller, required more intensive site preparation to perform as well as the larger bare-root stock. However, when we matched seedlings with less disparity in shoot size, first-year survival and growth were greater for container seedlings on two sites in the Ouachita Mountains (Brissette and Barnett 1989, 1992). We attributed the initial superior field performance of container seedlings to larger root systems and overall better shoot-to-root balance.

For reforestation, the use of half-sib family seed collections, rather than seed orchard mixes, has been increasing across the Southern United States for the past several years. One advantage of maintaining family identity is that it is possible to reduce variation in rates of seed germination and seedling growth in the nursery. Thus, nursery culture can be tailored to individual families, or groups of families, to grow seedlings of higher quality than possible when a bulked seed collection is sown. Similar growth advantages can be achieved when outplanting is by family as well. While producing and planting loblolly pine seedlings by family is now common, it is much less so for the other southern pines.

We designed this experiment to test whether stock type and half-sib family interact to affect field performance of shortleaf pine seedlings planted on typical reforestation sites in the Ouachita Mountains. Brissette and Barnett (1989, 1992) reported the 1st- and 3rd-year results of this study. This paper reports results through 10 years after planting, with emphasis on latter-year results.

MATERIALS AND METHODS

Family Selection and Seed Handling

Seed collections were made in the autumn of 1985 at the U.S. Department of Agriculture, Forest Service, Ouachita and Ozark seed orchard located near Mount Ida, AR. The seed orchard is organized by geographic sources. Separate blocks in the orchard consist of selections from the Ozark National Forest and the east and west sides of the Ouachita National Forest. Six half-sib families, two from each geographic source, were used in this study. Seed processing was done at the Forest Service's, Southern Research Station laboratory in Pineville, LA. The seeds were stratified for 35 days before sowing in the nursery.

Bare-Root Seedling Production

Staff of the Weyerhaeuser Company, Magnolia Forest Regeneration Center in southwest Arkansas grew the bare-root seedlings. The seeds were sown in mid-April 1986 using a Weyerhaeuser-designed precision vacuum seeder, which sowed eight parallel drills across the nursery beds. A germination rate of 90 percent was assumed, and enough seeds were sown to achieve a seedling density of about 23 per square foot. The two outside drills were planted with a seed orchard mix. The study families were assigned at random to the interior drills and rerandomized for each of seven replications; each replication was 50 feet long. In addition, seedlings were grown for several other

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

studies. Nursery cultural practices, such as fertilization and root pruning, were applied based on the best judgment of the nursery manager. Top pruning was not done. Seedlings were carefully hand-lifted on February 2, 1987, and kept in cold storage (approximately 38 °F) until planted.

Container Seedling Production

Container seedlings were grown at the Forest Service laboratory in Pineville, LA. The container volume was approximately 6.1 cubic inches, and density was about 46 per square foot. Containers were filled with a 1:1 peat-vermiculite medium and hand-seeded 1 week after the bare-root seeds were sown. The containers were in trays of 98; each tray held a single half-sib family, and there were 5 replications of each family.

The containers were kept in a greenhouse for 2 weeks until germination was complete. They were then moved to raised benches outside in full sunlight where the seedlings were grown and allowed to harden off. Except for having been grown outside, the seedlings received the cultural regime recommended by Barnett and Brissette (1986).

Planting Sites

The plantings were on two typical national forest sites in Arkansas; one on the Magazine Ranger District (RD) of the Ozark National Forest, about 18 miles southwest of Russellville, the other on the Winona RD of the Ouachita National Forest, about 40 miles southeast of Russellville and about 25 miles west of Little Rock. Although most of the Ozark National Forest is in the Boston Mountains, the Magazine RD is south of the Arkansas River and, therefore, in the Ouachita Mountains. Both sites are on gently rolling to rolling terrain with shallow, rocky soils. They had been clearcut harvested and site prepared as part of commercial operations. Both sites were ripped during site preparation. Ripping involves pulling vertical blades spaced about 8 feet apart through the soil to a depth of 18 to 20 inches. This is a process that has been shown to improve seedling water relations after outplanting and to increase height and diameter growth (Wittwer and Dougherty 1986).

On the Magazine RD site, container seedlings were planted on December 10, 1986, and the bare-root stock on February 11, 1987. On the Winona RD site, container seedlings were planted on December 9, 1986, and the bare-root seedlings on February 11, 1987. A 25-seedling row plot in 6 blocks at each planting site represented each stock type by family combination.

Measurements and Analyses

We analyzed data for each site separately using analysis of variance. The design at both locations was a randomized block with six blocks and a factorial arrangement of treatments in split plots. Block and stock type were in the whole plots, and family and the stock type × family interaction were in the subplots. The experimental units were the 25-tree plots.

Response variables were both measured and calculated. After the first growing season, survival, total height, and groundline diameter were measured. At the end of three growing seasons, survival and total height were measured. After five growing seasons, survival, total height, and diameter at breast height (d.b.h.) were measured, and at 10 years, survival and d.b.h. were measured and basal area (BA) calculated. Because BA combines survival and growth, it is a measure of the degree of site occupancy.

Survival data were transformed using the arc sine of the square root of the proportional value. This transformation ensures that the proportions are close to normally distributed with homogeneous variance (Freese 1967). Three linear contrasts were used to determine differences in mean performance among the geographic sources: (1) east Ouachita vs. west Ouachita, (2) east Ouachita vs. Ozark, and (3) west Ouachita vs. Ozark.

RESULTS AND DISCUSSION

Early Results

When outplanted, the bare-root seedlings had greater mean height and root-collar diameter than the container seedlings (table 1). However, the container seedlings had

Table 1—The effects of stock type on field performance of shortleaf pine seedlings 3, 5, and 10 years after outplanting on two sites in the Ouachita Mountains

	3 years		5 years			10 years		
Site/stock type	Survival	Height	Survival	Height	D.b.h.	Survival	D.b.h.	BA[a]
	percent	*feet*	*percent*	*feet*	*inches*	*percent*	*inches*	*ft²/acre*
Magazine RD								
Bare-root	92b[b]	5.0b	92a	9.9b	1.3b	90a	3.7a	43.7a
Container	96a	5.6a	94a	10.6a	1.5a	92a	3.8a	47.3a
Winona RD								
Bare-root	93b	3.4b	91b	7.1b	0.9b	91b	3.3b	36.2b
Container	98a	4.1a	97a	7.9a	1.0a	96a	3.6a	44.3a

BA = basal area; RD = ranger district.

[a] Each stock type x family plot was 25 trees planted at 8- by 8-foot spacing. Plot basal area was divided by 0.04 to obtain the basal area per-acre values.

[b] At each site, values followed by the same letter are not significantly different ($P = 0.05$).

greater mean root volume and a more favorable shoot-to-root balance than the bare-root stock. After one growing season at both field locations, survival of all families from both stock types exceeded 94 percent. The container seedlings grew larger than the bare-root seedlings. Although container seedlings were planted 2 months earlier than the bare-root stock, the difference in planting date was expected to have limited effect on initial seedling performance. Soil temperatures were low enough that little root growth could occur during this winter period (Brissette and others 1988). Among families, groundline diameters differed on one site, and family and stock type interacted in their effects on height on the other site (Brissette and Barnett 1992).

Survival

After 3 years on both sites, survival of container seedlings was significantly greater than survival of bare-root stock. The interaction of stock type and family and differences among families were not significant for survival at either site at age 3 and older. Because there were no significant interactions of stock type and family, in subsequent evaluations we combined family data.

At ages 5 and 10, the small differences in survival on the Magazine RD site were not statistically significant, but survival remained at 90 percent or higher. However, the container seedlings maintained greater survival than the bare-root on the Winona RD site through year 10.

Growth

There were no significant interactions between stock type and family at either site at year 3 or subsequent measurements for height or d.b.h. Differences in growth occurred on the Magazine RD site through 5 years with container stock performing best. At 10 years, there were no differences in d.b.h. between container and bare-root treatments at the Magazine RD location.

As was the case with survival on the Winona RD site, d.b.h. of container-grown seedlings was significantly greater than of bare-root stock. Calculations of BA, which incorporate both survival and d.b.h., showed significant differences on the Winona RD area. Both heights and diameters show that growth was better at the Magazine RD location, indicating Winona RD was the poorer of the two sites. Stock type differences, however, were greater at Winona RD, confirming results from earlier studies that container stock outperforms comparable bare-root material on poor sites (Goodwin 1980, South and Barnett 1986).

Height differences among families were statistically significant, reflecting the fact that the two tallest families differed from the three shortest families.

CONCLUSIONS

High-quality bare-root or container shortleaf pine seedlings will survive well on prepared sites in the Ouachita and Ozark Mountains. However, container stock generally performs better than bare-root stock, especially on poorer sites where both survival and growth are reduced. The superior performance of container stock probably is due to larger root systems and better balanced seedlings.

Differences in seedling morphology suggest that half-sib families of shortleaf pine are different enough that maintaining family integrity during seedling production will improve overall quality of planting stock. Differences among families that were observed at planting were maintained throughout the 10 years of growth regardless of stock type. It is interesting to note that the seedlings grown from the more northern Ozark seed source consistently produced smaller plants than those from the two Ouachita sources.

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COMPARISON OF PLANTING BAR AND HOEDAD PLANTED SEEDLINGS FOR SURVIVAL AND GROWTH IN A CONTROLLED ENVIRONMENT

John C. Adams and William. B. Patterson[1]

Abstract—In the Western Gulf Region of the United States, the traditional tool for planting loblolly pine (*Pinus taeda* L.) has been the dibble (planting bar). In the past decade an increasing number of acres have been planted with the hoedad. In areas where both tools were and are used, discussion about the superiority of one tool over the other for survival and subsequent growth have been on-going. This study was initiated to determine if the seedlings survived and grew better when planted with one tool or the other, when other planting variables were minimized. Survival, first- and second-year height, groundline diameter, first-year root weight, and first and second-year growth was found to be the same. There were no differences between the dibble and hoedad, and these were not different from the check, which was a planting hole made with a posthole digger. Planting failures using these tools can probably be traced to improper planting technique or improper handling of the seedlings prior to planting and not the tool in use.

INTRODUCTION

In the last 10 years in the United States approximately 27.2 million acres or an average of 2.7 million acres per year, were planted with trees. In 1996, 11 states planted more than 100,000 acres. All but two of these states were in the southern region of the country. Of these, the Western Gulf States of Alabama, Mississippi, Louisiana, Texas, and Arkansas planted 876,000 acres (Moulton and Snellgrove 1997). The majority of these acres were planted to conifers and most were planted with loblolly pine (*Pinus taeda* L.). The traditional hand planting tool in this region has been the dibble, also called a planting bar. However, a small but increasing number of acres are being planted by crews using the hoedad, a planting tool commonly used in the western states and in mountainous areas. In areas where both planting tools are used, there are questions about the effectiveness of one over the other in planting, survival and growth of seedlings. Planting crews using the hoedad claim better survival, better planting technique, faster planting, and better growth. Crews using the dibble have the opposite opinion. Foresters using these crews have mixed opinions about the effectiveness of the two planting systems.

The objective of any planting technique is to place a seedling in the ground with a minimum root distortion and in a manner to obtain good soil/root contact. There are a number of studies that address these two important issues (Adams and Vidrine 1989; Brissette and Barnett 1988; Gruschow 1959; Hay and Woods 1974; Lantz and others 1988; Woods 1980). The purpose of this study was to determine if there were any differences in survival and early growth between seedlings planted correctly with the hoedad and with the dibble.

METHODS AND PROCEDURES

A uniform group of commercially grown loblolly pine seedlings was selected for this study. Seedlings were randomly assigned to one of three treatments. Treatment one was planted with a dibble, treatment two was planted with a hoedad, and treatment three was planted with a manual type posthole digger. Seedlings planted with the posthole digger were considered a check or an optimum planting technique because the hole was made large with vertical cuts and little or no compaction on the sides of the planting hole. The seedlings were then placed in the hole, and the hole was back filled with soil. The dibble and the hoedad planted seedlings were planted essentially as outlined by Smith and others (1997) and are considered compression or modified-compression planting techniques, respectively. Seedling spacing was 38 x 38 cm.

The planting site was an abandoned nursery bed (not used for 3 years) containing a sandy loam soil. The bed was prepared by removing the grass cover and roto-tilling the bed. No fertilizer was added. The bed was divided into eight blocks with three randomly assigned treatments and seven seedlings per treatment. Seedlings from a bag containing 1,000 seedlings were sized into 3 groups. The largest and smallest size groups were eliminated and the seedlings for the study were chosen at random and assigned to treatments at random from the middle size group. The design was a randomized complete block. Grass and weed control were manually applied during the first year. Water was added once during the initial year during a period of extreme drought. In the second year, no weed/grass control was done nor additional water added.

Measurements for height and groundline diameter were taken 1 week after planting. At the end of the first growing season height and groundline diameter were again taken, and three seedlings from each treatment/block were removed and the roots excavated. The roots were washed, dried and weighed. At the end of the second growing season, groundline diameter and height were taken on the remaining trees. First-year growth was determined by calculating the difference between the initial measurements at planting and measurements at the end of the first year, and the second-year growth was determined by calculating the difference between the first growing season and second growing season measurements. Analysis of variance was done using a SAS statistical program (SAS 1985).

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Table 1—Initial, first and second year measurements for height, groundline diameter, and dry root weight for loblolly pine seedlings planted with three planting tools[a]

	Initial measurements		First year measurements			Second year measurements	
Treatment	GLD	Height	GLD	Height	Rt Wt	GLD	Height
	mm	*cm*	*mm*	*cm*	*g*	*mm*	*cm*
Dibble	0.49	26.44	16.94	79.23	29.45	34.50	190.0
Hoedad	0.48	27.46	16.48	77.64	30.46	33.30	185.1
Posthole	0.50	27.42	17.62	80.16	31.14	32.81	184.2

GLD = groundline diameter; Rt Wt = dry root weight.

[a] There were no significant differences among treatments at α = 0.05.

RESULTS AND DISCUSSION

Seedling measurements taken at planting time were nonsignificant and indicated that there were no differences among the different treatments (table 1) and blocks. Thus the sizing of seedlings and treatment assignments were effective, and initial seedling size was not a factor in the analysis for the growth variables.

Survival was 97 percent with mortality equally distributed among the treatments. All measurements for height, groundline diameter, and root dry weight at the end of the first year, and height and groundline diameter at the end of the second year were nonsignificant (table 1). Calculated growth (table 2) was also nonsignificant for all treatments during the two growing periods. There were no trends in the data, and the values among the treatments for each variable were essentially the same.

These data show that seedlings planted using proper technique with either the dibble, hoedad or posthole digger will produce equal results. The only observed difference among the three treatments was in the shape of the root systems that were excavated. The root systems from seedlings planted using the posthole digger had a more symmetrical root development with the first-order lateral roots developing in all directions from the taproot. The root systems from the seedlings planted with the dibble had a flattened root development on two sides with the lateral roots growing away from the compacted soil on the compression sides of the planting hole. The hoedad-planted root system was intermediate in that the root was flattened on one side, the side compressed by the blade, with the lateral roots uniformly extending 180 degrees from the compressed side of the planting hole. These morphological differences in root development had no effect on the survival and growth, above and below ground, of the loblolly pine in this study. This root distortion may not be persistent as the tree continues to grow. When the seedlings were excavated at the end of the first growing season some lateral roots were beginning to break through the compressed sides formed by the planting tools.

Table 2—Ground line diameter and height growth of loblolly pine seedlings planted with tree planting tools[a]

	Growth 1st year		Growth 2d year	
Treatment	GLD	Height	GLD	Height
	mm	*cm*	*mm*	*cm*
Dibble	16.45	52.79	17.56	110.77
Hoedad	16.00	50.18	16.82	107.36
Posthole	16.84	52.72	15.46	103.84

GLD = ground line diameter.

[a] There were no significant differences among treatments at α = 0.05.

CONCLUSIONS

Poor field results with either the dibble or hoedad as a planting tool are not the result of the tool in use but rather the technique used or more likely the manner that the seedlings were handled prior to and during the planting operation. Human nature to take the easiest path often results in improper seedling management such as wind exposure of roots, short root pruning and improper seedling placement (depth and position) by the tree planters. The result is poor seedling performance.

Resource managers responsible for planting should look at storage, planting technique and handling of seedlings rather than the instrument used to make the hole when trying to determine the cause of failures in planting operations.

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THE RESPONSE OF BAREROOT LOBLOLLY PINE SEEDLINGS TO THE AMOUNT AND TIMING OF NITROGEN FERTILIZATION IN THE NURSERY

Hans Williams, Karen Woodard, and Tim Stewart[1]

Abstract—A nursery study was conducted to observe the effects of altering the amount of nitrogen fertilizer at each application on bareroot loblolly pine (*Pinus taeda* L.) seedling morphology, survival and growth. The treatments were an equal amount of fertilizer applied each time, an increasing amount each time, and a schedule characterized by low amounts, high amounts, and low amounts. Six applications of ammonium nitrate (32.5 percent N) were applied between June and August 2000, and for all treatments, a total of 169 kg N per ha was applied. In addition, for each growing season treatment, the seedlings were treated either in October or November with a one-time application of 56 kg N per ha or 113 kg N per ha as ammonium nitrate. The seedlings were lifted in January 2001, for morphology measurements and field planting. The seedlings treated with an increasing amount of N during the growing season had greater foliage, stem and root weights. Seedlings treated with 113 kg N per ha in October had the largest root collar diameters. First-year survival exceeded 90 percent for all treatments. First-year height growth was greatest for the seedlings that received 113 kg N per ha in October in the nursery.

INTRODUCTION

Wakeley's (1954) morphological grades for loblolly pine continue to serve as useful guidance for growing the optimum southern pine seedling. However, bareroot loblolly pine seedling production philosophy appears to have changed from one of achieving few seedlings smaller than Grade 3 at lifting (less than 3.2 mm root-collar diameter) to one of achieving a high proportion of seedlings greater than Grade 1 at lifting (greater than 4.8 mm root-collar diameter). Boyer and South (1988) 15 years ago reported that 50 percent of the southern pine nurseries sampled produced fewer than 5 percent Grade 1 seedlings. Recently, South (2000) defined morphologically improved loblolly pine seedlings to be those grown at low seedbed densities in the nursery with half the population having a root-collar diameter (RCD) at lifting greater than 5 mm and none less than 3 mm, a more fibrous root system, but not taller than seedlings with a RCD of 3.9 mm. Lowering seedbed density is an effective means of increasing the proportion of seedlings with RCD greater than 5 mm (Caulfield and others 1987). Results from experiments also indicate manipulating nitrogen (N) fertilization timing and amounts in combination with seedbed density can influence seedling morphological characteristics (Brissette and Carlson 1987, Kormanik and others 1998, Switzer and Nelson 1963).

A study was conducted to observe the morphology and field response of bareroot loblolly pine seedlings treated in the nursery with different amounts of N applied at each application while still maintaining the total amount applied during the growing season. In addition to the growing season treatments, the seedlings were treated with two different amounts of N applied in October or November.

METHODS

The study was conducted at the Temple-Inland Clyde-Thompson Forest Tree Nursery located near Jasper, TX. On May 5, 2000, seed from one, half-sibling family were sown in the nursery bed at a rate to achieve a density of 269 seedlings per m^2. The seedlings were raised using the cultural practices typical for the nursery, except for the growing season N and fall N treatments. Four nursery beds were used in the study. Each nursery bed represented a replication of the growing season N and fall N treatments.

The growing season N treatments consisted of applying a total of 169 kg N per ha over six applications using one of three different protocols. The N source was ammonium nitrate (AN). The first protocol, referred to as "Operational", involved applying 28.2 kg N per ha at each application for the six applications. The "Increasing" treatment consisted of two applications at 9.4 kg N per ha, two applications at 18.8 kg N per ha, one application at 37.6 kg N per ha, and one at 75.1 kg N per ha. The "Low-Hi-Low" treatment consisted of 9.4, 18.8, 75.1, 37.6, 18.8, and 9.4 kg N per ha. The first of the six N applications was on June 1, and the last application was on August 9.

The growing season N whole plots were divided into five subplots representing the five fall N treatments. One subplot received no fall N application. In October, two subplots were treated with 56 or 113 kg N per ha as AN. In November, the two remaining subplots were treated with 56 or 113 kg N per ha as AN.

The seedlings were lifted in January 2001, placed in polyethylene-lined storage bags, and transported to Stephen F. Austin State University. The seedlings were placed in cold storage (4 °C) for about 1 week until planted. Twenty-five seedlings were randomly selected from each nursery replication and treatment combination for field planting. The seedlings were hand-planted near Etoile, TX on February 2, 2001. The soil at the planting site is a Woodtell very fine sandy-loam (Fine, montmorillontic, thermic Vertic Hapludalfs). Site preparation prior to planting included chopping, subsoiling, and bedding. An aerial application of

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

an imazapyr, triclopyr, and glyphosate solution was applied in September 2000, to control woody and herbaceous plants. The site was fertilized with diammonium phosphate at a rate of 280 kg N per ha in November 2000. In March 2001, about 6 weeks after planting, the site was treated with an aerial application of hexazinone to control herbaceous plants.

The dependent variables measured after lifting the seedlings in the nursery were seedling height, RCD, stem oven-dry weight, root oven-dry weight, and needle oven-dry weight. Percent foliar N concentration was determined prior to the fall N treatments and at lifting. Percent survival, total height, height growth and ground-line diameter were measured after the first growing season following planting.

The growing season N and fall N treatments were applied using a randomized complete block split-plot experimental design with four replications. The main effects were the growing season N and fall N treatments in the nursery. The whole plots were the growing season N treatments, and the subplots were the fall N treatments. The experimental design of the field planting was the same as the nursery design. Analysis of variance was conducted to test for statistical differences between the growing season N treatments, the fall N treatments, and their interactions for the dependent variables measured. Statistical differences are discussed at the 5 percent Type I error rate. Results from the data analysis indicated that the interaction between growing season N treatments and fall N treatments were not statistically significant. As a result, only main effect means will be presented in the results.

RESULTS

The differences in mean percent foliar N between the growing season N treatments or the fall N treatments were not statistically significant for the August 2000, or January 2001, sampling dates (table 1). When measured in August 2000, about 2 weeks after the last fertilizer application, the foliage of seedlings receiving the "Increasing" growing season N treatment seemed to have higher N concentrations when compared to the other growing season treatments ($P > F = 0.0552$). However, when measured in January, they had the lowest N concentrations. The foliage of seedlings treated with a fall N application appeared to have had slightly higher N concentrations than the seedlings treated with no fall N application.

Table 1—Percent foliar N concentration of bareroot loblolly pine seedlings used in the nursery nitrogen nutrition study

N treatment	August 16, 2000[a]	January 30, 2001[b]
Growing season[c]		
Operational	2.01	1.54
Increasing	2.18	1.46
Low-Hi-Low	1.82	1.54
(P > F)	0.0552	0.4487
Fall		
None		1.44
October-56 kg N/ha		1.59
October-113 kg N/ha		1.51
November-56 kg N/ha		1.53
November-113 kg N/ha		1.49
(P > F)		0.6638

[a] Means determined two weeks after final growing season N application.

[b] Means determined on seedlings lifted from the nursery.

[c] Operational = 28.2 kg N per ha at each application for six applications. Increasing = 9.4, 9.4, 18.8, 18.8, 37.6, and 75.1 kg N per ha. Low-Hi-Low = 9.4, 18.8, 75.1, 37.6, 18.8, and 9.4 kg N per ha.

Table 2—Mean morphology, at time of lifting, of bareroot loblolly pine seedlings used in the nursery N nutrition study

N treatment	Height	Root-collar diameter	Weights		
			Stem	Foliar	Root
	cm	*mm*	*g*		
Growing season[a]					
Operational	31.4	6.2	2.2	3.0	1.3
Increasing	32.6	6.3	2.6	3.4	1.8
Low-Hi-Low	32.2	6.1	2.9	2.9	1.4
(P > F)	0.7329	0.6107	0.0098	0.0018	0.0003
Fall					
None	31.6	6.1	2.3	3.1	1.4
Oct-56 kg N/ha	33.1	6.2	2.5	3.1	1.5
Oct-113 kg N/ha	31.6	6.6	2.5	3.3	1.7
Nov-56 kg N/ha	32.8	6.2	2.3	3.1	1.4
Nov-113 kg N/ha	31.3	5.3	2.2	2.9	1.4
(P > F)	0.3314	0.0123	0.3891	0.0878	0.0595

The seedlings were lifted from the nursery in January 2001.

[a] Operational = 28.2 kg N per ha at each application for six applications. Increasing = 9.4, 9.4, 18.8, 18.8, 37.6, and 75.1 kg N per ha. Low-Hi-Low = 9.4, 18.8, 75.1, 37.6, 18.8, and 9.4 kg N per ha.

Mean seedling height and RCD, at the time of lifting, were similar regardless of growing season N treatments (table 2). The differences measured in seedling biomass between the growing season N treatments were statistically significant. The seedlings treated with the "Increasing" treatment had heavier stem, foliar, and root oven-dry weights. The root-collar diameter differences observed at lifting between the fall N treatments were statistically significant. The seedlings treated in October with 113 kg N per ha had the greatest mean RCD. The differences for mean height and seedling biomass observed between the fall N treatments were not statistically significant. Although not statistically significant, it may be worthy to note that the seedlings treated with the 113 kg N per ha in October seemed to have the heaviest root systems ($P > F = 0.0595$).

First-year survival after planting exceeded 90 percent for all treatments (table 3). First-year total height, height growth and ground-line diameter were not statistically different between growing season N treatments. The differences observed in first-year height growth between fall N treatments were statistically significant. The seedlings treated with 113 kg N per ha in October exhibited the greatest first-year height growth.

CONCLUSIONS

The loblolly pine seedlings treated in the nursery during the growing season with an increasing amount of N had the greatest biomass at the time of lifting. Kormanik and others (1994) tested an N fertilization schedule for loblolly pine seedlings similar to the "Increasing" treatment. Their regimen produced seedlings with good shoot to root ratios and a high number of first-order lateral roots. The seedlings treated in the nursery with 113 kg N per ha in October had the greatest RCD at lifting and the best first-year height growth. Sung and others (1997) and Irwin and others (1998) also have reported positive results for southern pine seedlings treated in the fall with a N fertilizer. The field planting will be measured for several more years in order to observe whether the nursery treatments will have a lasting effect on seedling growth. The study has been repeated for a second year at the same nursery, and a similar N fertilizer study has been done at another nursery that uses a different form and schedule of fertilization.

ACKNOWLEDGMENTS

We gratefully acknowledge Temple-Inland Forest Products, Inc. for providing the funding and in-kind support for this research project.

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Table 3—First-year mean percent survival and growth of bareroot loblolly pine seedlings used in the nursery N nutrition study

Nursery N treatment	Survival	Total height	Height growth	Ground-line diameter
	percent	*cm*		*mm*
Growing season				
Operational	94.4	59.7	35.8	14.3
Increasing	94.0	61.1	37.8	15.4
Low-Hi-Low	92.9	60.5	39.3	10.2
(P > F)	0.7887	0.7714	0.6182	0.1568
Fall				
None	94.0	60.5	37.4	14.8
Oct-56 kg N/ha	92.6	58.2	34.4	14.6
Oct-113 kg N/ha	94.3	63.4	41.5	16.1
Nov-56 kg N/ha	93.3	59.5	36.3	14.1
Nov-113 kg N/ha	94.7	60.6	38.4	15.2
(P > F)	0.7479	0.5430	0.0083	0.1178

The seedlings were hand-planted in February 2001 and measured on September 21 and 22, 2001.
Operational = 28.2 kg N per ha at each application for six applications; Increasing = 9.4, 9.4, 18.8, 18.8, 37.6, and 75.1 kg N per ha; Low-Hi-Low = 9.4, 18.8, 75.1, 37.6, 18.8, and 9.4 kg N per ha.

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PERFORMANCE OF SLASH PINE BARE-ROOT SEEDLINGS AND CONTAINERIZED ROOTED CUTTINGS PLANTED ON FIVE DATES IN LOUISIANA

Alper Akgul, Michael G. Messina, Alan Wilson, and Joe Weber[1]

Abstract—Landowners are interested in extending the normal planting season, as well as the comparative field performance, of nursery bare-root seedlings and containerized rooted cuttings. The effect of seasonal planting dates on field performance of two stock types of slash pine (*Pinus elliottii* Engelm.) was examined. Slash pine bare-root seedlings (BRS) and containerized rooted cuttings (CRC) were hand planted in September, November, January, March and April in 2000-2001, 2001-2002, and in 2002-2003 on three poorly drained silt loam sites in western Louisiana. Stock types were planted in adjacent row plots and treated identically after planting. Thus far, mean survival of CRC is consistently high at 96 percent, whereas BRS survival is significantly lower at 78 percent and highly variable across planting dates and years. Height growth of trees planted in September, November, and January was significantly higher than that for trees planted in March and April.

INTRODUCTION

Originally restricted to 3 million ha, slash pine's range has been extended by planting to more than 5 million ha at present (Ezell and Moorhead 2000). Bare-root planting stock is primarily used for planting the southern pines (Barnett and Brissette 1986, Brissette and others 1983), and this is normally restricted to the dormant season, late November through early March, to ensure increased survival through reduced planting shock. There is also an escalating interest in using rooted cuttings as planting stock for pines (Stelzer and others 1998). Vegetative propagation can deliver planting stock of higher genetic quality that may increase yield and shorten rotations (Weber and Stelzer 2000). However, research to date on the relative performance of rooted cuttings and bare-root southern pine seedlings have yielded mixed results (Foster and others 1987, Stelzer and others 1998). Rooted cuttings can be grown either as containerized or bare-root. Many studies have shown that planting containerized stock can greatly extend the planting season (Barnett and McGilvray 1993), to year-round in some cases (Malinauskas and Sukhotskas 1996). It can also raise the utilization rate of cuttings because of less falldown in the nursery. The objective of this study was to compare the survival and growth of slash pine bare-root seedlings and containerized rooted cuttings when planted on five different annual planting dates.

MATERIALS AND METHODS

Study Sites

Two locations in Beauregard Parish and one location in Calcasieu Parish in southwestern Louisiana were planted for this study. The soils at all three sites are very deep, poorly drained, silt loam Alfisols on nearly level to very gently sloping terraces. The climate is warm and humid. Average annual temperature is 19.3 °C and annual precipitation is 1,494 mm (date for DeQuincy, LA, 1940-90). The study sites, previously planted with slash pine stands, were clearcut and mechanically bedded with a combination plow in 2000. Prior to planting, sites were sprayed with triclopyr and glyphosate to control competing vegetation. After planting, hexazinone and sulfometuron methyl was applied to control herbaceous vegetation and to promote uniformity across sites.

Planting Stock and Study Establishment

Planting stock tested in this study were bare-root seedlings (BRS) and containerized rooted cuttings (CRC) of slash pine. The BRS were produced through standard nursery culture at the Beauregard Nursery near Merryville, LA. The CRC were produced by Boise Corporation at their seed orchard near Evans, LA. Cuttings were harvested from less than 3-year-old slash pine hedges. CRC were full-sib and BRS were half-sib in the 2000-2001 planting season. They had one parent in common, whereas both CRC and BRS were full-sib from the same family in the 2001-2002 planting season. Both CRC and BRS were hand planted at 1.8- by 3.4-m spacing. BRS were lifted and planted on the same day. All trees were fertilized at planting with diammonium phosphate at the equivalent of 225 kg per ha.

Study Design and Statistical Analysis

Each location was planted on five different dates (September, November, January, early March, late April) in three successive years (2000-2001, 2001-2002, 2002-2003). Data from the first two planting seasons are discussed in this paper. The design was a split-plot with planting date as the main plot and stock type as the subplot. Trees were planted in 20-tree rows with 10 replications per site-year. This layout required planting 18,000 trees. Analysis of variance was performed using the General Linear Model procedure of SAS for a split-plot design (SAS Institute 1997). Percentage survival data were arcsin transformed before analysis, but untransformed means were presented for clarity. Mean separations were tested using the Duncan's new multiple range test (α = 0.05) method.

Measurements

Basic measurements included survival, height, groundline stem diameter (GLD), and diameter at breast height (d.b.h.). Survival was determined for all plantings every September. Tree size was measured for all plantings every January.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

RESULTS AND DISCUSSION

Survival

Survival data for the 2000-2001 plantings (fig. 1), measured in September of 2002, showed that CRC had a significantly ($P < 0.0001$) higher survival (95 percent) than did BRS (79 percent). Time since planting ranged from 17 to 24 months at the September 2002 survival assessment. BRS survival varied from 87 percent for the April planting to as low as 64 percent for March. However, CRC survival varied from 98 percent for the November planting to 87 percent for April.

Survival of the 2001-2002 plantings (fig. 2), also assessed in September 2002, showed that CRC (98 percent) significantly ($P < 0.0001$) out-performed BRS (77 percent). Time since planting ranged from 5 to 12 months at the September 2002 survival assessment. BRS survival varied from 95 percent for the November planting to as low as 52 percent for September. Alternatively, CRC survival varied little, from 99 percent for January to 96 percent for April. To summarize, CRC survival was significantly ($P < 0.0001$) higher than that for BRS in both years.

Height, GLD and D.B.H.

Trees planted in the 2000-2001 season were in the field between 9 to 16 months when total height and groundline stem diameter data were collected in January 2002. CRC planted in September 2000 through March 2001 were taller than BRS, but there was no height difference between BRS and CRS planted in April 2001 (fig. 3).

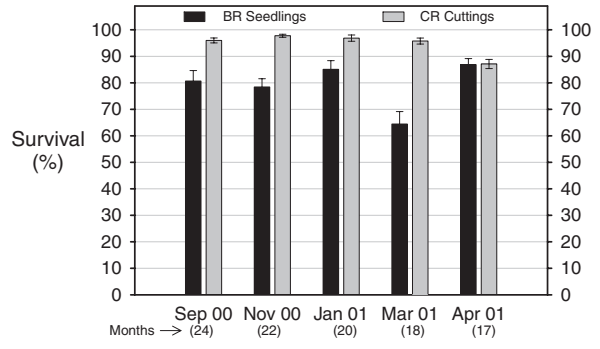

Figure 1—Survival of 2000-2001 plantings. Error bars indicate one standard error. Numbers in parentheses show months since planting.

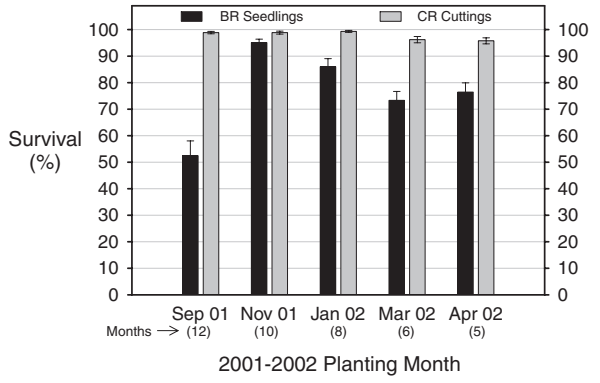

Figure 2—Survival of 2001-2002 plantings. Error bars indicate one standard error. Numbers in parentheses show months since planting.

Height and GLD of trees planted in the 2000-2001 planting season were measured again in January 2003 (figs. 4 and 5). Time since planting varied from 28 months for September 2000 to 21 months for April 2001. Tree height averaged for both stock types varied in the order September > November

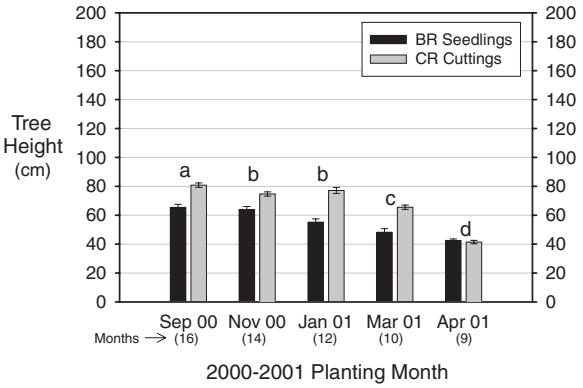

Figure 3—Mean height of 2000-2001 plantings measured in January 2002. Error bars indicate one standard error. Numbers in parentheses show months since planting. Letters are statistical differences ($\alpha = 0.05$) for months as a main effect.

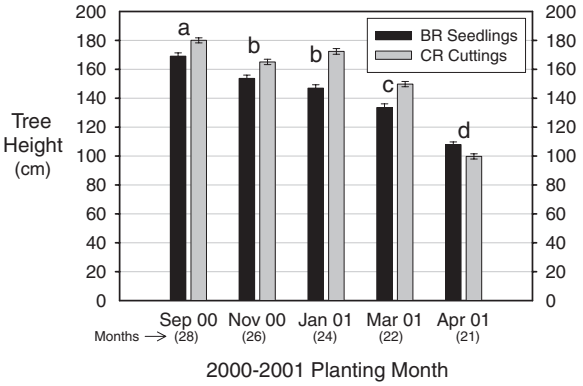

Figure 4—Mean height of 2000-2001 plantings measured in January 2003. Error bars indicate one standard error. Numbers in parentheses show months since planting. Letters are statistical differences ($\alpha = 0.05$) for months as a main effect.

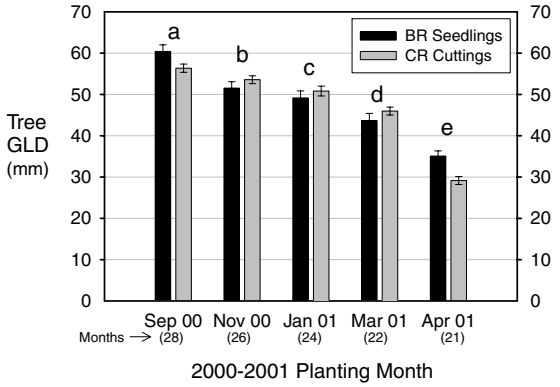

Figure 5—Mean groundline stem diameter of 2000-2001 plantings measured in January 2003. Error bars indicate one standard error. Numbers in parentheses show months since planting. Letters are statistical differences ($\alpha = 0.05$) for months as a main effect.

= January > March > April (fig. 4). CRC were significantly (α = 0.05) taller than BRS in every planting month except April, when there was no difference.

Similarly, GLD varied in the order September > November > January > March > April across stock types after 21 to 28 months in the field (fig. 5). However, GLD differed between stock types only in trees planted in September and April when bare-root seedlings had significantly (α = 0.05) larger GLD than did CRC, 28 and 21 months after planting, respectively.

Height and GLD of trees planted in 2001-2002 season were measured in January 2003. CRC were significantly (α = 0.05) taller than BRS, except for April plantings for which there were no differences. CRC had significantly (α = 0.05) higher GLD than did BRS for all months (fig. 6).

Diameter at breast height was also measured for those trees that had a d.b.h. of at least 1.5 cm. There were no d.b.h. differences between stock types or planting months after 21 to 28 months in the field (fig. 7). As expected, early plantings had a larger percentage of trees that had developed a d.b.h. than did the later plantings (fig. 8).

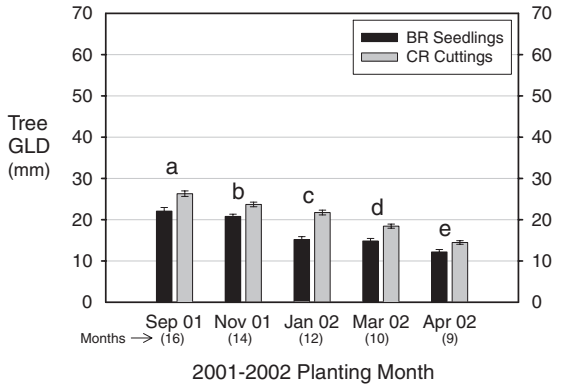

Figure 6—Mean groundline stem diameter of 2001-2002 plantings measured in January 2003. Error bars indicate one standard error. Numbers in parentheses show months since planting. Letters are statistical differences (α = 0.05) for months as a main effect.

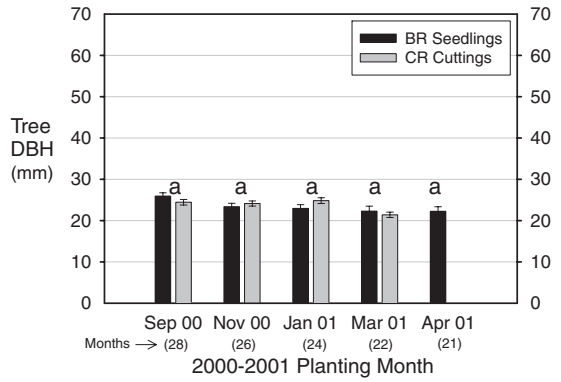

Figure 7—Mean diameter at breast height of 2000-2001 plantings measured in January 2003. Error bars indicate one standard error. Numbers in parentheses show months since planting. Letters are statistical differences (α = 0.05) for months as a main effect.

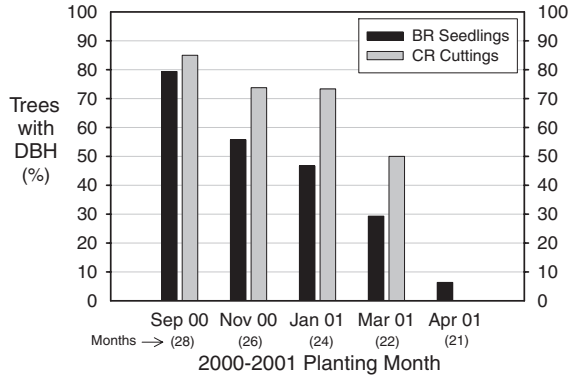

Figure 8—Percentage of trees that had developed DBH. Numbers in parentheses show months since planting.

Total Plot Height

Height data for the 2000-2001 plantings were weighted with survival data by calculating a total plot height through summing the heights of all existing trees on a plot in January 2003 (fig. 9). CRC had higher total tree plot height than did BRS for all planting months except for April. Total plot height varied little among September, November and January plantings for CRC. For BRS, September plantings had the highest total plot height, whereas the spring plantings (March and April) had the lowest.

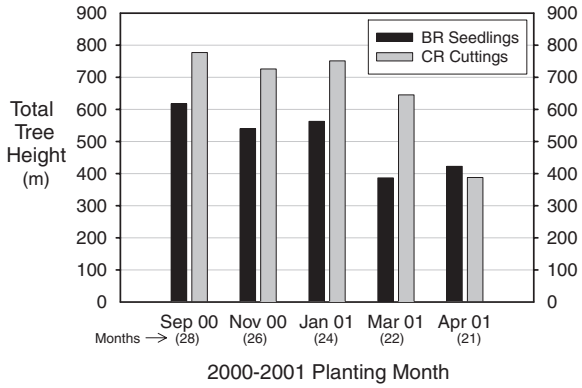

Figure 9—Total plot tree height of 2000-2001 plantings measured in January 2003. Numbers in parentheses show months since planting.

DISCUSSION

CRC planted between September 2000 and March 2001 had greater height and GLD growth compared to BRS at the end of the first full growing season in January 2002. Measurements in January 2003 show that 21 to 28 months after planting, CRC were taller than BRS. However, the GLD difference between stock types was negligible in the second year. BRS planted in September 2000, the oldest in the field, had the highest mean GLD in January 2003. The difference in heights but the lack of difference in GLD between the stock types suggests a difference in tree form in these young trees. Some studies with radiata pine showed that vegetative propagules had straighter boles with less taper (Libby and others 1972, Spencer 1987). However Stelzer and others (1998) did not find any differ-

ence in height, d.b.h., volume or stem taper between the rooted cuttings and seedlings of 10-year-old loblolly pine although they reported early age propagule differences.

Height difference between stock types was also lessening at the end of the second growing season. BRS height increment averaged across all five planting times was greater in the second growing season than that of CRC, but CRC had greater height increment in the first year. Foster and others (1987) found that rooted cuttings were significantly taller at ages one and four although the seedlings had higher relative growth rates. These results may indicate that the differences in early years might virtually disappear as the trees mature.

We suspect that CRC's greater height and GLD increment in the first growing season is an indication of CRC's quick adaptation to its environment after being planted. Whereas second-year growth of BRS was higher than that of CRC, the often much lower survival of BRS makes total area-wide production less than that of CRC. Some research indicated the higher survival of cuttings compared to seedlings (Frampton and others 2002, Stelzer and others 1998). Struve and others (1984) found that trees from rooted cutting origin had greater wood volume per hectare per year relative to trees from seedlings, and they attributed this to the higher survival rates of trees from rooted cuttings.

Survival and growth data indicate thus far that use of CRC can extend the planting season by allowing planting as early as September. Extending the planting season by planting later into the spring thus far has produced more disappointing results than planting early. Our data suggest that CRC, with its superior and steady survival and often better height growth, has thus far out-performed BRS.

ACKNOWLEDGMENTS

We thank Boise Cascade Corporation for funding this experiment. We also thank the Texas A&M Forest Science Laboratory personnel for their assistance.

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FOUR PINE SPECIES GROWN AT FOUR SPACINGS ON THE EASTERN HIGHLAND RIM, TENNESSEE, AFTER 30 YEARS

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Abstract—In 1966, four pine species [loblolly pine (*Pinus taeda* L.), Virginia pine (*P. virginiana* Mill.), shortleaf pine (*P. echinata* Mill.) and eastern white pine (*P. strobus* L.)] were planted at four spacings (6 x 6 foot 9 x 9 foot 12 x 12 feet and 15 x 15 feet) on the eastern Highland Rim near Tullahoma, Tennessee, to evaluate their growth and development. Survival for all species at 6 x 6 foot in 1996 was significantly lower (39 percent) than at the other three spacings (58 to 64 percent). Eastern white pine had significantly higher stand cubic foot volume and economic value than the other three species. Loblolly pine had significantly higher stand volume and economic value than shortleaf pine and Virginia pine. Volume for loblolly pine was highest at 6 x 6 feet (8,820 cubic feet per acre) and lowest at 15 x 15 feet (4,807 cubic feet per acre). Long-existing markets have favored loblolly pine, although markets have recently developed in the area of this study for eastern white pine.

INTRODUCTION

"The Barrens" is an area on the Eastern Highland Rim southeast of Nashville and northwest of Chattanooga. Estimates of its area range from a quarter to a half million acres (Clebsch and Pyne 1995, Shanks 1958). Its forests are predominately hardwoods and are generally low in volume and poor in quality. The dominant species include scarlet oak (*Quercus coccinea* Muenchh.), chestnut oak (*Q. prinus* L.), post oak (*Q. stellata* Wangenh.), blackjack oak (*Q. marilandica* Muenchh.), and southern red oak (*Q. falcata* Michx. var. *falcata*), with a few hickories (*Carya* spp.), elms (*Ulmus* spp.), and ash (*Fraxinus* spp.). Forest composition and appearance reflects a combination of natural factors, particularly a fragipan at 20 to 30 inches, and human causes, including fire, both Native American and settler, grazing, and high grading. In 1961, the University of Tennessee acquired a 860 acre tract in the Barrens southeast of Tullahoma, which became the Highland Rim Forestry Experiment Station (HRFES). During the next few years, Dr. Eyvind Thor established a number of pine evaluation studies at this location, including the species-spacing study reported in this paper.

METHODS AND MATERIALS

The topography of the HRFES is flat to gently rolling. The climate typically is warm humid summers and mild winters. Annual precipitation is 57.6 inches, with 12.5 inches during July and 6.2 inches in January. Average winter temperature is 42 °F, while average summer temperature is 71 °F. There are 196 frost-free days. The soil of the site is Dickson silt loam (fine-silty, siliceous, thermic Glassic Fregindults), which is typical in the Barrens area. As indicated above, it has a fragipan which limits permeability to air, water, and roots. Soils are acidic with low organic matter content and nutrients.

In this study, four species (loblolly pine, shortleaf pine, Virginia pine and eastern white pine) were planted at four spacings (6 x 6, 9 x 9, 12 x 12, and 15 x 15 feet) in a split-plot design with four replications. In each replication, species were randomly assigned to 2-acre square plots. The main plots were divided into four ½- acre square plots to which each of the four spacings was randomly assigned.

In 1965, the native forest on the site was harvested, cull trees injected with 2,4-D and the area mist-blown to kill the herbaceous vegetation. In the late winter of 1966, 2-0 eastern white pine seedlings and 1-0 seedlings of the other species were planted. The eastern white pine and shortleaf pine seedlings were from TVA's Clinton, Tennessee, nursery, while the loblolly pine and Virginia pine seedlings came from Hiwassee Land Company's Rose Island nursery.

Measurements were taken on trees in the interior ¼-acre plot to minimize edge effects. To have about the same number trees measured for each spacing, all trees in the ¼-acre plots were measured in the 15 x 15-foot spacing, while in the three closer spacings only trees in systematically selected rows were measured. Diameter was measured with a diameter tape; height was measured with a clinometer and 100-foot tape on surviving trees.

Individual tree volume was calculated with equations developed by Clark and others (1991). Coefficients for the upper Coastal Plain were used for loblolly pine, shortleaf pine, and Virginia pine, while coefficients for the Appalachian Mountains were used for eastern white pine. Value was estimated by getting sawtimber and topwood volume for trees 10 inches and larger d.b.h. Sawtimber volume between a ½-foot stump and a 6-inch upper-stem diameter and topwood volume between a 6-inch and a 4-inch upper-stem diameter were calculated. For pulpwood trees with d.b.h. less than 10 inches, volume from a ½-foot stump to a 4-inch upper-stem diameter was calculated. Volumes were converted using 160 cubic feet per thousand board feet

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

(MBF) and 90 cubic feet per cord (Toennisson and Hadden 1992). Pulpwood value was calculated using 1998 delivered price of $66.88 per cord (Tennessee Department of Agriculture Forestry Division 1998). Sawtimber values were determined using $200 per MBF for yellow pines and $280 per MBF for eastern white pine (Tennessee Department of Agriculture Forestry Division 1998).

Plot values were calculated for each variable with SAS Proc MEANS. A mixed model ANOVA was performed with SAS to determine interactions of main effects and compare differences between the means of subplots across blocks using pairwise contrasts. Tukey-Kramer's test was performed for all variables with a probability level of $P < 0.05$.

RESULTS AND DISCUSSION

Survival

Results from 22 years (1988) and 30 years (1996) after establishment are compared and reported. Survival did not differ significantly among species at 22 years or 30 years (table 1). Although significant differences would be expected, given the range in survival, there was considerable variation among the plots. Survival for trees at 6 x 6 foot was significantly less than at the other three spacings for both measurements. Although not significantly less, survival at 9 x 9 foot was numerically less than the two wider spacings at 30 years, perhaps due to increased competition.

The effect of spacing on survival varied among species. No trend was seen for shortleaf pine at either measurement (table 1). Survival for Virginia pine was not affected by spacing at 22 years but had a significant difference between the 6 x 6 foot spacing and the other spacings at 30 years. Survival in eastern white pine and in loblolly pine decreased with spacing for both measurements. The low survival for loblolly pine at 15 x 15 feet at each measurement was influenced by very poor survival in one plot.

Tree Characteristics

The mean height of eastern white pine was significantly higher than loblolly pine, and both were significantly taller than shortleaf pine and Virginia pine (table 2). There were small, although significant, differences among mean heights by spacing within species; however, there was no trend with spacing within species. The d.b.h. of loblolly pine and eastern white pine were significantly larger than that of shortleaf pine and Virginia pine (table 2). For all species there was a marked increase in d.b.h. as spacing increased. Individual tree volume followed the trends of d.b.h. (table 2). Loblolly pine and eastern white pine were significantly larger than shortleaf pine and Virginia pine. Within each species, individual tree volume increased as spacing increased.

Individual tree value for eastern white pine was significantly higher than for the yellow pines (table 2). Loblolly pine was significantly higher than shortleaf pine and Virginia pine. This is the result of a greater price per MBF for eastern white pine and larger individual trees for eastern white pine and loblolly pine. Again, individual tree value for each species increased as spacing increased.

The only difference in 22 year results for individual tree means is that eastern white pine and loblolly pine were not different in height. At 22 years, the mean height of eastern white pine was 63 feet, while loblolly pine was 61 feet. At age 30, the heights were 78 and 73 feet, respectively.

Stand Characteristics

At 22 years, eastern white pine and loblolly pine had significantly more stand volume than shortleaf pine and Virginia pine (table 3). Stand volume decreased as spacing increased for all four species. The decrease in number of trees per acre with increasing spacing had a greater impact on stand volume than the increase in individual stem volume with increasing spacing.

The value of eastern white pine was significantly greater than the other three species. Loblolly pine was significantly more valuable than shortleaf pine and Virginia pine (table 3). Stand value decreased as spacing increased for all species, except eastern white pine where it peaked at 9 x 9 foot. This was due to considerably more eastern white

Table 1—Least squares estimates of percent survival by species and spacing 22 years and 30 years after planting for the species-spacing comparison near Tullahoma, TN

Species	Years since planting	Spacing (*feet*)[a] 6 x 6	9 x 9	12 x 12	15 x 15	Mean
Loblolly pine	22	54.90ef	62.50abcde	76.00abcde	64.95abcde	64.59A
	30	43.14efg	56.77abcde	73.00ab	64.40abcd	59.33A
Shortleaf pine	22	54.90bcde	67.19abcd	49.35ef	53.15cdef	56.15A
	30	65.36abcde	70.23abcde	66.87abcde	64.36abcde	49.51A
Virginia pine	22	65.36abcde	70.23abcde	66.87abcde	64.36abcde	66.70A
	30	29.26f	57.58abcde	62.34abcde	59.09abcde	52.07A
Eastern white pine	22	52.94def	75.52abcd	80.50ab	87.05a	74.00A
	30	40.20fg	63.02bcde	74.50ab	80.80a	64.63A
Mean	22	57.03B	68.86A	68.18A	67.38A	
	30	39.30B	58.40A	64.03A	63.79A	

[a] Lower case letters indicate significant differences among spacings and species within years since planting. Upper case letters indicate significant differences among species or among spacings.

Table 2—Mean tree dimensions by species and spacing 30 years after planting for the species-spacing comparison near Tullahoma, TN

Species	Tree dimension	Spacing (*feet*)[a]				
		6 x 6	9 x 9	12 x 12	15 x 15	Mean
Loblolly pine	Height(*feet*)	73c	70d	70d	73d	72B
	DBH(*inches*)	9.0gh	10.1ef	11.7bc	13.5a	11.1A
	Vol.(*cubic ft*)	17.2ef	21.1d	27.2c	38.4a	26.0A
	Value(*$*)	16.13fgh	22.36e	31.05d	45.70b	28.81B
Shortleaf pine	Height(*feet*)	60f	61ef	58gh	57gh	59C
	DBH(*inches*)	7.5i	8.6h	9.5fg	9.8fg	8.9B
	Vol.(*cubic ft*)	11.2hi	14.4fg	17.4def	17.6de	15.1B
	Value (*$*)	8.49i	12.33ghi	17.79efg	17.96ef	14.14C
Virginia pine	Height(*feet*)	62ef	63e	59fg	57h	60C
	DBH(*inches*)	69i	8.6h	10.0f	10.6de	9.0B
	Vol.(*cubic ft*)	8.8i	13.1gh	16.8ef	18.2de	14.2B
	Value(*$*)	6.45i	10.78hi	17.20efg	19.59ef	13.51C
Eastern white pine	Height(*feet*)	78ab	79ab	77b	79a	78A
	DBH(*inches*)	9.3fgh	11.0cd	12.2b	13.9a	11.6A
	Vol.(*cubic ft*)	18.2def	25.1c	31.4b	40.4a	28.8A
	Value(*$*)	22.90e	37.73c	49.86b	66.18a	44.17A

[a] Lower case letters indicate significant differences among spacings and species. Upper case letters indicate significant differences among species.

Table 3—Mean stand dimensions by species and spacing 22 years after planting for the species-spacing comparison near Tullahoma, TN

Species	Stand dimension	Spacing (*feet*)[a]				
		6 x 6	9 x 9	12 x 12	15 x 15	Mean
Lobloll pine	Volume[b]	6656a	4643c	4205cd	2915fg	4605A
	Value[c]	4923cd	4100de	4401d	3322f	4186B
Shortleaf pine	Volume	4442cd	3207f	1860hi	1331i	2710B
	Value	3214efg	2240hij	1594ijk	1144k	2025C
Virginia pine	Volume	4529cd	3390ef	2483gh	1628 l	3007B
	Value	3027fgh	2374ghi	2136ij	1480jk	2254C
Eastern white pine	Volume	6139ab	5680b	4270cd	3943de	5008A
	Value	5635bc	7070a	6132b	6119b	6239A

[a] Lower case letters indicate significant differences among spacings and species within years since planting. Upper case letters indicate significant differences among species.
[b] Stand volume is in cubic feet per acre to a 4 inch dob.
[c] Stand value is for sawtimber, topwood and pulpwood in $ per acre.

pine trees being of sawtimber size at the 9 x 9 foot spacing than at 6 x 6 foot.

Eastern white pine and loblolly pine again had significantly more stand volume than shortleaf pine and Virginia pine at 30 years (table 4). Stand volume decreased as spacing increased for three species. Virginia pine had significantly less volume at the 6 x 6 foot spacing than at the 9 x 9 foot spacing because of large mortality in three of the four replications.

At 30 years, as at 22 years, eastern white pine had the highest value, followed by loblolly pine and then shortleaf pine and Virginia pine (table 4). Stand value decreased with increasing spacing for loblolly pine and shortleaf pine. For eastern white pine and Virginia pine, value peaked at the 9 x 9 foot spacing. As at 22 years for eastern white pine, this was due to the number of sawtimber size trees in the 9 x 9 foot spacing. The drop in value for Virginia pine at the 6 x 6 foot spacing was due to the large mortality noted under stand volume.

Fiber from eastern white pine sawtimber tree tops and from pulpwood trees is used for products such as OSB, but not for pulp. Therefore, the values cited above may not be appropriate for locations that do not have eastern white pine pulpwood markets. Removing the value of eastern white pine pulpwood results in a considerable decrease in value at the 6 x 6 foot spacing and small decreases at the other three spacings (table 4).

Table 4—Mean stand dimensions by species and spacing 30 years after planting for the species-spacing comparison near Tullahoma, TN

Species	Stand dimension	Spacing (*feet*)[a] 6 x 6	9 x 9	12 x 12	15 x 15	Mean
Loblolly pine	Volume[b]	8820a	6471bc	6014c	4807d	6528B
	Value[c]	8245c	6857de	6863d	5715ef	6920B
Shortleaf pine	Volume	5980c	4369d	2452ef	1785f	3647C
	Value	4530fg	3736gh	2503ef	1830j	3150C
Virginia pine	Volume	3056e	4045d	3173e	2118f	3098C
	Value	2223hij	3317ghi	3249ghij	2275ij	2766C
Eastern white pine	Volume	8908a	8518a	7097b	6347c	7718A
	Value	11217b	12798a	11290b	10404b	11427A
	ST value[d]	7990	11241	10454	9884	9892

[a] Lower case letters indicate significant differences among spacings and species within years since planting. Upper case letters indicate significant differences among species.

[b] Stand volume is in cubic feet per acre to a 4 inch dob.

[c] Stand value is for sawtimber, topwood and pulpwood in $ per acre.

[d] Stand ST value is only for sawtimber in $ per acre; no statistical differences were calculated on sawtimber values.

RECOMMENDATIONS

Based on this study, loblolly pine and eastern white pine are recommended for planting on the Barrens of Tennessee. They had superior survival and growth when compared to shortleaf pine and Virginia pine. The choice between eastern white pine and loblolly pine needs to be based on markets. Although eastern white pine had more volume and may bring more money per MBF, markets for it are not as numerous as those for loblolly pine. Thus, the geographic location of the site to be planted and its proximity to markets can have a great impact on the choice of species.

Recent southern pine beetle infestations in east Tennessee have spread to the Eastern Highland Rim. They have totally infested the three yellow pine species in this study and also have started to infest the eastern white pine. Although eastern white pine is infested in severe southern pine beetle outbreaks, it is less likely to be affected in moderate infestations. This lower risk for eastern white pine should also be considered when selecting a species to plant.

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RECTANGULAR SPACING: AN ECONOMIC BENEFIT?

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Abstract—Many loblolly pine (*Pinus taeda* L.) plantations are established at row spacings of 8 to 12 feet, but some companies are now using rows spaced 14 to 18 feet apart. Wide rows reduce establishment costs when sites are bedded, ripped, or machine planted. The cost of chemicals is also reduced when treatments are applied in bands along the row. A growth and yield program (Ptaeda2.1V) was used to predict volume losses from planting in 14- to 20-foot rows. Results suggest that when a thinning (to a constant basal area) is conducted at age 15, a rectangularity ratio of 2:1 reduces the amount of sawtimber predicted at age 23 by only 1 to 2 percent when compared to a square spacing. The cost savings associated with wider rows results in a slight increase in net present value (NPV). Field trials are needed to verify the biological effects of wide rows on volume growth and branch size of plantations established with less than 600 trees per acre.

INTRODUCTION

Seedling stocking and row spacing can affect the long-term growth and economics of loblolly pine (*Pinus taeda* L.) plantations. Although many papers have been published on the effects of planting density, only a few have been published on the effects of row configuration, *per se*, on loblolly pine (Adams and Clason 2002, Sharma and others 2002a, 2002b). Row width can affect the level of crown closure, and planting density can affect the age at which particular product-size trees are achieved (Sharma and others 2002a). Due to a lack of historical data on row-configuration, many foresters have relied on intuition and have opted to plant trees in square (1-to-1 ratio) or with low rectangularity ratios (i.e. less than 2-to-1). However, when trees are planted at stockings greater than 800 trees per acre, rectangularity of 3-to-1 has little effect on height, d.b.h., crown ratio, crown length, crown width, and survival of 16-year-old loblolly pine (Sharma and others 2002a).

Publications have shown that rectangularity has no effect on pine growth (Lewis and others 1985, Sharma and others 2002a, Zhang and others 1996). Lewis and others (1985) found that basal area and cubic-foot volume were not reduced in spacings of 24 feet by 4 feet (24 x 4) and 48 x 2 when compared to spacings of 12 x 8. Obviously, the 24 x 4 and 48 x 2 configurations are far from conventional for pine management, but they do show that extremely high ratio configurations (6:1 and 24:1) do not necessarily reduce growth.

Planting 300 to 400 trees per acre not only reduces planting costs but can also provide a quicker and greater return on investment (Balmer and others 1975, Caulfield and others 1992, Harms and Lloyd 1981, Marty 1988). This is especially true when the pulpwood market is depressed. To date, little research has been conducted on rectangularity at planting densities less than 500 per acre. For example, at a density of 453 trees per acre, a 12 x 8 spacing may produce a 9-year-old tree with a 0.82-inch branch while a 16 x 6 spacing might produce a tree with a 0.86-inch branch (Adams and Clason 2002).

Fifty years ago, Wakeley (1954) recognized that wide rows could reduce establishment costs. For example, the cost of machine planting is directly affected by row width (Incoll and others 1979). Although less time is required to hand-plant 1,000 seedlings in wide rows (due to less walking distance), the cost savings might not be passed on to the landowner when tree planters are paid a set price per tree. Rectangular spacings of 2-to-1 are used for pine in New Zealand (Maclaren 1993) and Europe (Savill and others 1997) because of the decreased costs and increased accessibility. Intensively cultured, short-rotation hybrid poplar (*Populus* spp.) plantations are commonly planted in rectangular configurations to accommodate mechanized equipment (DeBell and Harrington 2002). Several industrial foresters in the South have been planting on rectangular ratios since the early 1980s. When no thinning is expected, some plant with row spacings of up to 20 feet. When thinning, wide rows could eliminate the need to remove entire rows since most bunchers and skidders would fit between the rows. Wide spacing would also reduce scraping against residual trees. Skidders or tractors could easily pass through the stand if they were conducting herbicide or fertilization treatments, once again reducing the amount of damage to residual trees.

This study was conducted to simulate the effect of rectangularity ratios of 3 to 4 on volume growth and Net Present Value (NPV) of a plantation that was thinned at age 15 and harvested at age 23.

METHODS

An individual tree distance-dependent growth and yield model (PTAEDA 2.1V) was used to project the growth and yield of loblolly pine (Burkhart and others 2001). Simulations were conducted using the average output from 5 seed numbers (i.e. 400; 800; 1,100; 1,200; 1,500). Simulations involved two site productivity classes (site index 60 and 80 feet, base age 25) and three initial planting densities (i.e. 311, 436, 622 trees per acre). Site preparation costs were set at $100 per acre, and seedling cost was $40 per thousand. An annual tax of $2 per acre was

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

assumed for both sites. The cost of machine planting varied as a function of the number of passes required to plant an acre. It was assumed that at a row spacing of 8.37 feet, it would cost $40 an acre to plant and $40 an acre to conduct a banded herbicide application. The square root of 43,560 yields a side length of 208.71 feet. The number of passes it takes to machine plant an acre was determined by dividing 208.71 by 8.3666 (i.e. 24.95 passes per acre). Therefore, each pass costs $1.60. The planting costs and banded herbicide application costs associated with different between row distances were calculated by multiplying the required number of passes per acre times $1.60. For example, using a between row distance of 20 feet yields $16.73 per acre for machine planting [(208.71/20)*1.60].

Trees greater than 10 inches in diameter at breast height were considered sawtimber, and it was assumed 20 percent of all sawtimber sized trees had defects and were usable only as pulpwood. Thinnings (from below) were conducted at age 15, and stands were projected to age 23. Projected stands with site index (SI) of 60 and 80 were thinned back to basal areas of 60 and 80 square feet per acre, respectively.

In this analysis, pulpwood was valued at $15 per cord, and sawtimber was valued at $350 per thousand board feet. The economic analyses involved calculating NPV assuming a reforestation tax credit. This assumes that establishment of less than $10,000 can be amoritized over a 7-year period.

RESULTS

When compared to the square spacing, the rectangular spacing with ratios of 2 or less reduced production of sawtimber volume by only 1 to 2 percent (table 1). Row spacing of 14 feet tended to increase NPV (table 2). Generally, the NPV was greater when planting 311 trees per acre than when planting 436 or more trees per acre. The simulation indicated rectangularity had minimal effect on live crown ratio or height to the first live branch (table 1).

DISCUSSION

For both the low site and high site, the highest NPV was achieved by a low density (i.e. 311 trees per acre) and a rectangular spacing (14 x 10). However, the increase was only $3 to $6 more than the square spacing (11.8 x 11.8). The range of NPVs was much greater when planting at 622 trees per acre. At this initial spacing, values range from $46

Table 1—Predicted yields at age 23 for different initial spacings of loblolly pine on two sites

Initial	Row	Within	QMD	AH	Crown	Stem	Cord	Scribner	Cordthin
				Site index 60					
311	10	14	10.4	59.0	40.7	35.0	7.5	5327	4.3
311	11.83	11.83	10.4	59.0	40.7	35.0	7.4	5347	4.3
311	14	10	10.4	59.1	40.7	35.0	7.5	5315	4.3
311	20	7	10.3	58.6	40.5	34.9	8.8	4788	4.0
436	10	10	10.0	58.9	39.4	35.7	9.6	4517	5.9
436	14	7.14	9.9	58.8	39.4	35.7	10.0	4446	5.8
436	20	5	9.8	58.3	39.0	35.5	10.8	4013	5.1
622	7	10	9.6	58.9	38.3	36.4	11.0	3870	8.1
622	8.37	8.37	9.6	59.0	38.3	36.4	11.4	3836	8.0
622	10	7	9.6	59.0	38.2	36.4	10.9	3956	7.9
622	14	5	9.6	59.1	38.2	36.5	12.9	3396	9.0
622	17.5	4	9.3	58.3	37.7	36.3	13.2	3124	6.8
				Site index 80					
311	10	14	12.2	77.2	37.3	48.4	8.1	12486	9.1
311	11.83	11.83	12.2	77.3	37.3	48.5	8.1	12492	9.2
311	14	10	12.2	77.3	37.2	48.5	8.3	12428	9.0
311	20	7	12.1	76.9	37.1	48.4	8.2	12183	8.6
436	10	10	11.7	77.4	36.1	49.5	8.4	12110	12.7
436	14	7.14	11.7	77.5	36.0	49.6	8.5	12021	12.3
436	20	5	11.4	76.7	35.6	49.4	9.9	11320	10.9
622	7	10	11.1	76.8	34.8	50.1	9.2	11269	16.0
622	8.37	8.37	11.1	76.8	34.9	50.1	8.6	11325	16.4
622	10	7	11.1	76.7	34.8	50.0	8.6	11378	16.2
622	14	5	11.0	76.6	34.6	50.0	8.9	11301	15.2
622	17.5	4	10.8	75.9	34.4	49.8	10.5	10471	14.0

Initial = number of seedlings planted per acre; Row = feet between rows; Within = feet between trees within a row; SI = site index (base age 25) in feet; QMD = quadratic mean diameter; AH = average height of all trees in feet; Crown = crown ratio; Stem = height to first live branch; Cord = number of cords per acre to a 4 inch top at age 23; Scribner = board feet per acre; Cordthin = number of cords removed per acre to a 4 inch top at age 15.

Table 2—Costs and Net Present Values for various initial spacings of simulated loblolly pine stands thinned at age 15 and harvested at age 23

Initial	Row	Within	Seedling	Herb/planting	Disccost	Disccord	Discct	Discsaw	NPV
				Site index 60					
311	10	14	$12.44	$33.47	$204.10	$29.37	$26.91	$488.10	$340.29
311	11.83	11.83	12.44	28.28	193.73	28.98	26.91	489.96	352.12
311	14	10	12.44	23.90	184.97	29.45	26.91	487.01	358.40
311	20	7	12.44	16.73	170.63	34.71	25.04	438.68	327.80
436	10	10	17.42	33.47	209.08	37.54	36.93	413.93	279.32
436	14	7.14	17.42	23.90	189.95	39.11	36.30	407.41	292.87
436	20	5	17.42	16.73	175.61	42.49	31.80	367.71	266.38
622	7	10	24.89	47.81	245.23	43.04	50.57	354.61	202.99
622	8.37	8.37	24.89	40.00	229.61	44.77	49.95	351.49	216.59
622	10	7	24.89	33.47	216.54	42.73	49.57	362.50	238.25
622	14	5	24.89	23.90	197.42	50.81	56.33	311.16	220.89
622	17.5	4	24.89	19.12	187.86	51.99	42.44	286.28	192.85
				Site index 80					
311	10	14	12.44	33.47	204.10	31.65	57.21	1144.05	1028.81
311	11.83	11.83	12.44	28.28	193.73	31.97	57.58	1144.67	1040.49
311	14	10	12.44	23.90	184.97	32.75	56.58	1138.80	1043.16
311	20	7	12.44	16.73	170.63	32.20	53.58	1116.32	1031.47
436	10	10	17.42	33.47	209.08	33.06	79.49	1109.65	1013.13
436	14	7.14	17.42	23.90	189.95	33.46	76.99	1101.47	1021.96
436	20	5	17.42	16.73	175.61	38.88	68.47	1037.20	968.94
622	7	10	24.89	47.81	245.23	36.13	100.39	1032.60	923.89
622	8.37	8.37	24.89	40.00	229.61	33.93	102.65	1037.69	944.65
622	10	7	24.89	33.47	216.54	33.77	101.65	1042.54	961.41
622	14	5	24.89	23.90	197.42	34.95	95.26	1035.51	968.30
622	17.5	4	24.89	19.12	187.86	41.23	87.50	959.45	900.33

Initial = number of seedlings planted per acre; Row = feet between rows; Within = feet between trees within a row; SI = site index (base age 25) in feet; Seedling = cost of seedlings per acre; Herb/planting = is the cost per acre to do banded herbicide applications and for machine planting; Disccost = discounted costs of all operations; Disccord = discounted revenue of pulpwood harvested at age 23 to a 4 inch top; Discct = discounted revenue of pulpwood thinned at age 15 to a 4 inch top; Discsaw = discounted revenue of sawtimber harvested at age 23; NPV = net present value.
A 6 percent interest rate was used for all analyses.

on the low site (from $193 to $238) to $68 on the high site (from $900 to $968).

The minimal effect of rectangular spacing (i.e. 14 x 10 or 14 x 7.1) on volume production is similar to the results reported from unthinned stands. Zhang and others (1996) and Sharma and others (2002a, 2002b) found that when planting more than 800 trees per acre, growth of unthinned 16-year-old loblolly pine was not significantly affected by rectangularity. Although Adams and Clason (2002) reported the diameter of 9-year-old loblolly was 7.2 inches for a 12 x 8 spacing and 7.0 inches for a 16 x 6 spacing, this difference was not significantly different.

Some factors associated with rectangular spacing are difficult to quantify economically. For example, fifth-row-thinnings do not need to be performed. Wide distances between rows allows foresters more management flexibility when conducting selective thinnings. In addition, there may be a reduction in damage to stems during intermediate operations. Wide rows will aid habitat for certain wildlife species. In dense stands with closed canopies, understory vegetation production is small (Lewis 1989, Wolters 1973). Wide rectangular spacings will provide a longer duration of time where the overstory canopy does not completely shade out the understory. Of course, wide spacing between rows of pines was first adopted in the South by agroforesters (Lewis and others 1985).

CONCLUSIONS

Rectangular spacings are used as alternatives to square spacings to reduce regeneration and intermediate silvicultural operation costs, and to increase return on investment. It also provides many benefits that are difficult to quantify economically such as increases in wildlife habitat and easy access to the stand. It is not the point of this paper to provide an optimal planting configuration for all sites, stockings, thinning regimes, and species. Rather, the objective of this paper was to examine the possible economic advantage associated with planting trees in wide rows. Results from this preliminary investigation suggest that rectangular spacings can be used to increase return on investment.

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Ecophysiology

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PREDICTING SOIL CO_2 EFFLUX RATES IN THE LOBLOLLY PINE ECOSYSTEM ACROSS THE REGION

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Abstract—Patterns in soil CO_2 efflux (E_c) over a short rotation were examined using a chronosequence approach on South Carolina Coastal Plain and Virginia Piedmont loblolly pine (*Pinus taeda* L.) stands. E_c was measured over an entire year in four separate age classes at both measurement locations in order to capture spatial and temporal variation in E_c over a 20+ year rotation. Within each stand, spatial variability was also accounted for by taking measurements both near the base of the tree and between rows. We found that soil temperature (at 10 cm) was the major driver of E_c on both locations. We also observed a strong positive stand age effect on E_c in Virginia Piedmont stands and a weak negative relationship between age and E_c in the South Carolina Coastal Plain stands. Variation in site preparation intensity between the two locations may influence the rate of carbon turnover.

INTRODUCTION

Researchers have cited a continued need for better understanding and quantifying the role forest management may play in soil carbon turnover over a range of stand types and ages (Banfield and others 2002, Field and Fung 1999, Liski and others 2002, Turner and others 1995, Woodwell and others 1983). Inherent site characteristics along with forest management practices that commonly alter microclimate and productivity may directly impact E_c. However, the literature provides no clear consensus concerning the effect of forest management and E_c. Previous investigators observed an increase (Gordon and others 1987, Londo and others 1999, Lytle and Cronan 1998), decrease (Striegl and Wickland 1998), or no change (Edwards and Ross-Todd 1983, Fernandez and others 1993, Toland and Zak 1994) in E_c following clearcut harvesting. Differences among ecosystems and experimental designs may account for inconsistencies in the literature; however, the distinct differences found among investigators suggest that generalizations across all forest types are not appropriate when developing carbon budgets. Frequently, E_c and soil carbon turnover have been shown to increase with harvest intensity (Edwards and Ross-Todd 1983, Lee and others 2002, Londo and others 1999). Also, Mallik and Hu (1997) showed that soil respiration rates corresponded to the amount of organic matter incorporated into the soil during site preparation in boreal mixedwood forest.

In this report, we present information regarding the relationship between E_c and soil temperature, soil moisture, stand age, and measurement location within a stand for two locations differing in site quality, climate, and cultural practices. Our overall objective was to develop predictive models that would be used to estimate E_c from managed loblolly pine (*Pinus taeda* L.) stands across the region. We hypothesized that E_c would be primarily related to soil temperature.

MATERIALS AND METHODS

Loblolly pine stands located on the South Carolina Coastal Plain and the Virginia Piedmont were chosen since these locations represent two extremes in terms of site productivity, cultural practices, and climate within the managed range of loblolly pine. Because we wished to examine the variability of E_c over space and time, taking into account possible effects due to stand age, we chose stands that covered ages typical of a short rotation. Four replications consisting of 4 age classes were selected at each study location (South Carolina and Virginia) for a total of 16 study plots per location. Stands were grouped according to the following age classes: 1, 4 to 6, 8 to 12, and 18-to 25-years-old since planting (at beginning of the data collection). Replications had similar soil and drainage characteristics and were in close proximity (< 1 km) to each other.

Within each study plot, E_c measurements, soil temperature from 0 to 10 cm, and soil moisture from 0 to 10 cm were taken concurrently near the base of the tree and between rows (two measurement positions) in order to account for intrasite variability described by Pangle and Seiler (2002). Three sets of measurements, considered subsamples, were taken at each replication x ageclass x measurement position. Subsamples were averaged for analysis. Measurements began in April 2000 on the Virginia location and continued monthly through March 2001. Measurements in South Carolina began in August 2001 and continued bimonthly through the following August. An additional January 2003 measurement date in South Carolina was added in order to cover the range in temperature variability that is representative of the study location. A total of 96 measurements (on each parameter described below) were collected on a sampling date (4 replications x 4 ageclasses x 2 measurement positions x 3 subsamples). The resulting datasets for the South Carolina and Virginia locations include 768 and 1,152 sets of measurements, respectively. Our sampling allowed us to capture variability due to location,

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

season, temperature, moisture, stand age, and measurement position within a stand.

Multiple linear regression analysis was used to assess the statistical relationship between E_c and potential explanatory variables including soil temperature, soil moisture, stand age, site index, and measurement position for each location.

RESULTS AND DISCUSSION

Our statistical modeling results show that a majority of the variance in E_c from both locations is explained by soil temperature, stand age, measurement position, and soil moisture. Soil temperature consistently explains the most variance in E_c from both locations. The common model developed separately for the Virginia Piedmont and the South Carolina Coastal Plain has the following form:

$$E_c = B_0 + B_1(\text{Soil Temperature}) + B_2[\text{LN}(\text{Soil Temperature})] + B_2[\text{LN}(\text{Stand Age})*(\text{Soil Temperature})] + B_3(\text{Measurement Position}) + B_4(\text{Soil Moisture}) \quad (1)$$

The above model explains 54 percent and 77 percent of the variance in E_c on the South Carolina Coastal Plain and the Virginia Piedmont, respectively. The following simplified model, including only soil temperature and stand age drivers, explains 50 percent and 70 percent of the variance in E_c on the South Carolina Coastal Plain and the Virginia Piedmont, respectively:

$$E_c = B_0 + B_1(\text{Soil Temperature}) + B_2[\text{LN}(\text{Soil Temperature})] + B_3[\text{LN}(\text{Stand Age})*(\text{Soil Temperature})] \quad (2)$$

Statistical comparisons of like coefficients associated with common models for each study location indicate that the relationship of E_c to model drivers differs between the South Carolina Coastal Plain and Virginia Piedmont. Therefore, a single model with identical coefficients is not appropriate for the two locations.

We observed a strong positive relationship between E_c and soil temperature on both study locations (fig. 1). However, we observed a different relationship between stand age and E_c on the South Carolina Coastal Plain in comparison to the Virginia Piedmont. Specifically, the Virginia Piedmont displayed a strong positive effect of age on E_c, while E_c from the South Carolina location exhibited a weak negative response to stand age. Stand age generally has a weak or inconsistent effect on E_c in forest stands according to previous reports (Ewel and others 1987, Klopatek 2002, Pyker and Fredeen 2003). However, variable management intensities may provide a better explanation of the differences we observed on the two locations. Generally, E_c increases as management intensity increases (Edwards and Ross-Todd 1983, Lee and others 2002, Londo and others 1999). Specifically, the intensity of site preparation and the amount of woody debris incorporated into the soil have been shown to have an effect on E_c and may explain why we observed higher rates in one-year-old South Carolina stands, in which slash was incorporated into beds during site preparation. The strong positive relationship

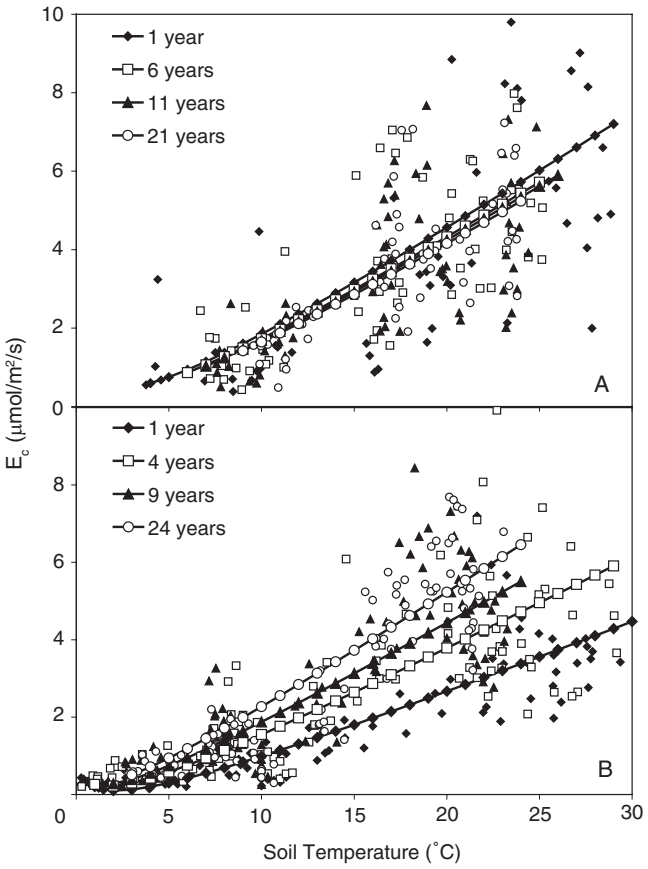

Figure 1— Relationship between soil temperatures (10 cm depth) and E_c in four age classes of loblolly pine stands located on the South Carolina Coastal Plain (A) and the Virginia Piedmont (B). Lines with symbols represent the linear regression line relating E_c to soil temperature for a given stand age class. Ages given represent the average age of the four replicated ageclasses.

between stand age and E_c in Virginia stands may be explained by increases in respiring root volume associated with stand age and a possible depression in microbial respiration rates following prescribed burning since several of the Piedmonts stands were burned for site preparation. Investigators have shown that burning reduces microbial respiration in European coniferous forests (Fritze and others 1993, Hernandez and others 1997, Pietikainen and Fritze 1993, Pietikainen and Fritze 1995); however, there have been no studies conducted in loblolly pine.

Dissimilarities in site quality, management, and climate between study locations likely impact the contribution of root and microbial respiration to E_c differently over a rotation. In the South Carolina Coastal Plain, the total contribution of microbial respiration to E_c likely increased with bedding, a relatively intensive site preparation. In one-year-old stands, E_c is greater on the South Carolina Coastal Plain relative to Virginia Piedmont across temperatures (fig. 1). The difference in E_c between the two locations is likely due to differences in the contribution of microbial respiration since one-year-old stands from both locations have minor contributions from respiring roots early in the rotation. With increasing stand age, coarse woody debris incorporated into beds was consumed,

probably by microbes (data not shown). After coarse woody debris was exhausted as a source of carbon substrate, microbial respiration rates probably dropped, which may account for the slight reduction in E_c we observe with increasing stand age. The amount of E_c attributed to root respiration probably increases over time, which is consistent with the increase in root biomass we observe as stands age (data not shown). The preceding statement implies that inverse shifts in root respiration and microbial respiration offset changes in E_c over time in the coastal plain stands. In the Virginia Piedmont, a different trend likely occurred over time. The less intensive site preparation, which included prescribed burning in some stands, probably had no effect or decreased microbial respiration. Since the forest floor was not greatly disturbed in the Virginia Piedmont stands during site preparation, the contribution of microbial respiration to E_c may be impacted less in young stands. Respiring root biomass growth and possibly recovering microbial populations impacted by burning may account for the positive trend in E_c we observed in Virginia stands with age. A direct comparison of E_c between the two locations in greater than 20-year-old stands shows that E_c across temperatures is similar, indicating that any initial effects due to site preparation are nearly undetectable towards the end of the rotation.

Using equation 2, we generated predicted E_c values which were subsequently superimposed on E_c datasets from unrelated studies conducted on the South Carolina Coastal Plain and the Virginia Piedmont (data not shown). We generally found good agreement between our predicted values and actual E_c values, suggesting that our relatively simple model containing soil temperature and stand age drivers may explain a substantial amount of variance in E_c within the given areas of the region for which each model was developed.

CONCLUSIONS

A single predictive model for E_c must account for regional differences in cultural practices since site preparation and management intensity appear to affect carbon turnover rates. Specifically, bedding may enhance microbial driven carbon turnover early in a rotation on the South Carolina Coastal Plain while less intense soil disturbances and burning during site preparation on the Virginia Piedmont may minimally affect or depress microbial respiration. Since total root respiration likely increases with stand age on both locations, shifts in the contribution of microbial and root respiration partially explains the different relationship we observed between E_c and age on the two study locations.

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BELOWGROUND PROCESSES IN NITROGEN FERTILIZED COTTONWOOD AND LOBLOLLY PINE PLANTATIONS

Kye-Han Lee and Shibu Jose[1]

Abstract—We measured soil respiration, fine root biomass production, and microbial biomass along a fertilization gradient (0, 56, 112, and 224 kg N ha^{-1} per year) in 7-year-old cottonwood and loblolly pine plantations, established on a well-drained, Redbay sandy loam (a fine-loamy, siliceous, thermic Rhodic Paleudlt), in northwest Florida. Annual soil respiration rate was significantly greater in cottonwood (781 g C m^{-2} per year) than in loblolly pine (692 g C m^{-2} per year). Nitrogen (N) fertilization had a significant negative effect on soil respiration in cottonwood, but no effect was observed in loblolly pine stands. Annual fine root production was significantly greater in cottonwood (221 g m^{-2} per year) than that in loblolly pine (144 g m^{-2} per year) without N fertilization effect. Microbial biomass, however, was reduced by N fertilization in both species. These results suggest that belowground responses to fertilization can vary widely between conifers and hardwoods.

INTRODUCTION

The potential response of aboveground biomass growth to fertilization is nearly always positive. However, belowground response to fertilization is often unclear in plantations and natural forests because of the uncertainty involved in quantifying root biomass. In addition to altering root growth and turnover rates, fertilization could also affect soil processes such as respiration, microbial activity, and soil pH. Nitrogen (N) fertilization of forest plantations has become increasingly important as an intensive management tool in recent years (Fox 2000). It has been speculated that intensive forest management may lead to a reduction in soil carbon (C), due partially to increased soil respiration (Harmon and others 1990). The few existing studies have found conflicting results, with one reporting an increase (Gallardo and Schlesinger 1994) and the other reporting a decrease (Haynes and Gower 1995). Since soil respiration results from two main sources, root respiration and the decomposition of organic matter and associated respiration of soil fauna, the conflicting results reported could be the result of fertilizer-induced differences in C fixation and allocation patterns among different tree species (Raich and Tufekcioglu 2000). Belowground C input through fine root production and turnover and associated microbial activity are well-documented processes in the C and nutrient cycling of forest ecosystems (Keyes and Grier 1981, McClaugherty and others 1982). Majdi and Kangas (1997) reported that a high input of N increased fine root mortality and decreased production and longevity, while addition of N-free fertilizer extended fine root longevity. In addition to the amount of belowground carbon, soil respiration could also be influenced by a number of other parameters, including the inherent and/or fertilizer-induced variation in soil physical and chemical properties, which may influence the quality and quantity of soil fauna. Microbial biomass has been shown to be a sensitive indicator responding quickly to environmental impacts. Zhang and Zak (1998) found that N fertilization increased microbial biomass and root growth. However, others have reported decreased soil microbial biomass in response to high rates of N fertilization (Smolander and others 1994). These conflicting results may be due to the differences in the initial status of the microbial communities, soil pH, organic matter, and soil nutrient contents. Though fairly large amounts of information exist on how forest stands and individual trees respond to nutrient input, many uncertainties and controversies exist on the belowground responses and on the interactions among various processes such as soil respiration, fine root production and microbial biomass in response to long-term fertilization. We utilized a 7-year-old fertigation trial with cottonwood (*Populus deltoides* Marsh.) and loblolly pine (*Pinus taeda* L.) to investigate the following questions: (1) how do soil respiration, microbial biomass, fine root production, and soil pH vary for hardwood vs. conifer stands (established on the same soil) along a N fertilization gradient, and (2) what are the interrelationships among the above mentioned variables and how do they vary between species?

MATERIALS AND METHODS

Study Site

This study was conducted in 7-year-old cottonwood and loblolly pine plantations established in 1995 on an agricultural field (16.2 ha) located in northern Santa Rosa County, FL (30°50´ N, 87°11´ W), U.S.A. The climate is temperate with mild winters and hot, humid summers. The soil is characterized as a well-drained, Redbay sandy loam (a fine-loamy, siliceous, thermic Rhodic Paleudlt). A drip irrigation system was run to apply water and N fertilizer (0, 56, 112, 224 N kg ha^{-1} per year) in the treatment plots during growing seasons for 8 consecutive years from 1995 to 2002. Three plots in each treatment were selected for this experiment.

Soil Respiration

We measured soil respiration monthly using the soda-lime technique (Edwards 1982) from June 2001 through May 2002 at three randomly selected locations in each plot. The measurements were conducted at the same locations during the study year. Cylindrical plastic buckets, 20 cm tall and 27.5 cm in diameter, were used as measurement chambers. An uncovered tin cup containing 60 g of oven-dried

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

soda-lime was placed under the inverted plastic chamber. After a 24-hour CO_2 absorption period, the tin cup was removed and oven dried at 105 °C for 24 hours to measure weight gain. Soil temperature and moisture were measured at 12 cm depth adjacent to each chamber during installation.

Fine Root Production

Monthly fine root (< 2 mm) production was determined by means of ingrowth core method at three randomly selected locations in each plot from June 2001 through May 2002. The ingrowth core method consists of removing a core to a depth of 30 cm by a sharp-edge steel corer with an internal diameter of 5.1 cm and refilling the hole with root free soil, which was taken from the same site and sieved through a 2 mm screen. The core was resampled after a month and the roots that had grown into the core counted as fine root production. The same hole was used for ingrowth sampling during the entire study year. Soil cores were wet sieved through a fine mesh screen, and all hand-sorted root fragments were considered fine root production. Roots were dried at 65 °C for 48 hours and weighed to ± 0.1 mg.

Microbial Biomass C

Soil microbial biomass C was measured by chloroform fumigation-extraction procedure (Vance and others 1987). Three soil cores (10 cm deep) were taken near the location for soil respiration measurement in each plot in September 2001. These soil samples were used for microbial biomass C, soil organic matter, and soil pH measurements. Sieved 50 g soil samples were placed in a 100 mL beaker and a 250 mL HDPE bottle for the fumigated and control samples, respectively. The fumigated samples were incubated in ethanol-free chloroform in evacuated desiccators for 24 hours at 25 °C. Fumigated and control samples were extracted with 100 mL of 0.5 M K_2SO_4, shaken for 1 hour, and filtered through Whatman No. 42 filter paper into 60 mL HDPE bottles. The extracted samples were acidified with phosphoric acid and frozen until analysis for dissolved organic C. Soil organic matter was determined by the ignition method using a 5 g dried soil, and soil pH was measured using a 1:5 soil-deionized water paste.

Statistical Analysis

The effect of treatments (species and fertilization) on soil respiration rate and fine root production was tested using an unequal two-way ANOVA; microbial biomass C, soil organic matter, and pH was tested using the General Linear Model procedure of SAS (SAS Institute, Cary, NC). If significant treatment effects were revealed ($\alpha = 0.05$), Tukey's studentized range test was used for mean separation. Possible effects of soil microbial biomass C, fine root production, soil organic matter, and soil pH on annual soil respiration rates were evaluated using Pearson correlation analysis (SAS Institute 1990).

RESULTS AND DISCUSSION

Soil Respiration

Annual soil respiration rates in this study ranged from 725 - 858 g C m^{-2} per year (average of 781 g C m^{-2} per year) under cottonwood to 647 - 720 g C m^{-2} per year (average of 692 g C m^{-2} per year) under loblolly pine stands and differed significantly ($P = 0.002$) between cottonwood and loblolly pine stands (table 1). N fertilization significantly affected soil respiration in cottonwood stands ($P = 0.008$) but had no effect in loblolly pine stands (figs. 1A, 1B). Similar ranges have been reported in a number of studies. Raich and Schlesinger (1992) reported a mean soil respiration of 647 and 695 g C m^{-2} per year from a wide array of temperate deciduous forests and coniferous forests, respectively. Annual soil respiration rate in loblolly pine was approximately 11 percent lower than that in cottonwood stands in our study, similar to a 10 percent reduction observed by Raich and Tufekcioglu (2000) while comparing deciduous and coniferous stands on identical soils. Temporal variation in soil respiration rates was closely related to soil temperature fluctuation in both species (fig. 2). Mean daily soil respiration rates displayed a significant exponential relationship with soil temperature; the relationship was stronger in cottonwood stands ($R^2 = 0.81$) than in loblolly pine stands ($R^2 = 0.51$) (fig. 3). Annual soil respiration rate in cottonwood stands was positively correlated with fine root biomass production (r = 0.64) and soil microbial biomass C (r = 0.87) and negatively correlated with soil pH (r = -0.81). In loblolly pine stands, however, annual soil respiration was positively correlated with fine root biomass production (r = 0.54) and soil organic matter content (r = 0.74). Since root respiration and associated microbial activity are two major sources of soil respiration (Keyes and Grier 1981, McClaugherty and others 1982), it is not surprising that soil respiration decreased along an increasing N fertilization in cottonwood.

Fine Root Production

Annual fine root production in cottonwood stands was 35 percent greater ($P < 0.0001$) than that in loblolly pine stands (table 1). This agrees with results by Aber and others (1985) and Steele and others (1997), who showed that hardwood forests have greater fine root biomass production than pine forests of similar age. In a recent study, Usman and others (2000) reported that fine root production was 44.6 percent higher in oak forests than in nearby pine forests in central Himalaya. Despite having a decreasing trend of fine root production in cottonwood and increasing trend in loblolly pine along an increasing soil N fertilization, no significant differences among the fertilization treatments were observed in either species (fig. 1). Annual fine root production ranged from 208 to 241 g m^{-2}

Table 1—Means of soil respiration, fine root production, and microbial biomass in cottonwood and loblolly pine plantations in northwest Florida[a]

Variable	Cottonwood	Loblolly pine
Soil respiration (g C m^{-2} per year)	780.8 (19.3)a	691.5 (24.2)b
Fine root production (g m^{-2} per year)	220.8 (28.5)a	144.2 (23.4)b
Microbial biomass (mg C kg^{-1} dry soil)	144.3 (19.5)a	122.2 (25.7)a

[a] Numbers in parenthesis are the standard error of the mean (n = 12). Different letters within a row indicate significant differences (Tukey HSD test, α = 0.05).

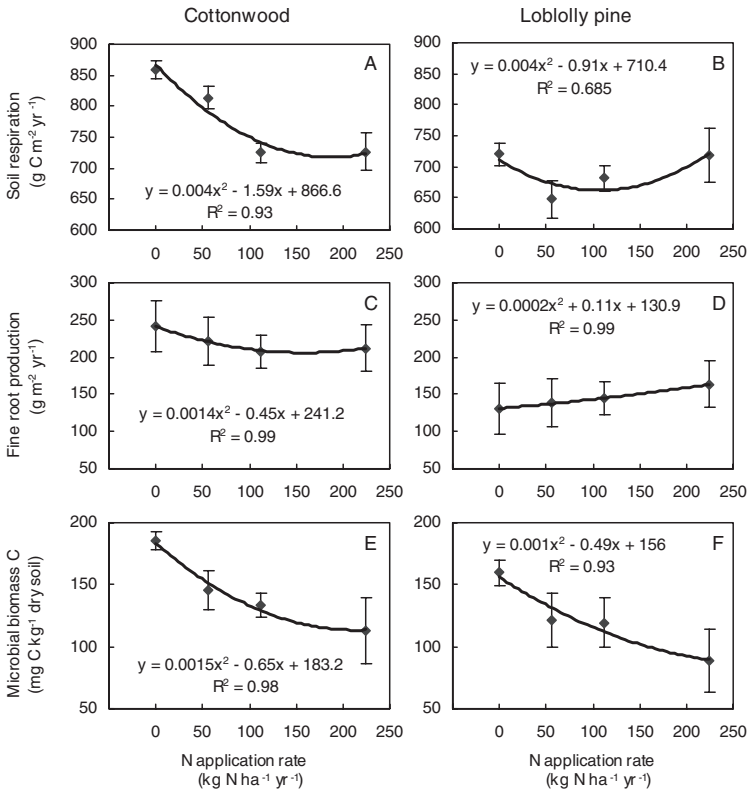

Figure 1—Effects of N fertilization rates on soil respiration (A and B), fine root production (C and D), and microbial biomass C (E and F) in cottonwood and loblolly pine plantations in northwest Florida. Vertical bars indicate standard error of the mean (n = 12).

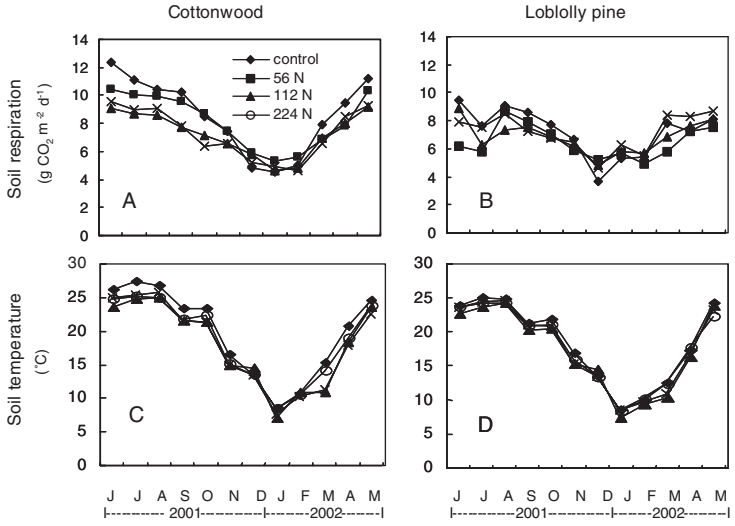

Figure 2—Mean monthly soil respiration rates in 7-year-old cottonwood (A) and loblolly pine (B) plantations along a fertilization gradient (0, 56, 112, and 224 kg N ha^{-1} per year), and soil temperature (C and D) at 12 cm depth under both species.

per year in cottonwood stands, and from 131 to 163 g m^{-2} per year in loblolly pine stands (figs. 1C, 1D). In comparison to other average fine root production estimates by ingrowth core methods, our estimation in cottonwood stands (221 g m^{-2} per year) was within the range of 147-254 g m^{-2} per year reported for temperate deciduous forests (Fahey and Hughes 1994, Hertel and Leuschner 2002); the 144.2 g m^{-2} per year in loblolly pine stands was also within the range of 120-200 g m^{-2} per year reported by Nadelhoffer and others (1985) and Aber and others (1985) for red pine plantations in Wisconsin.

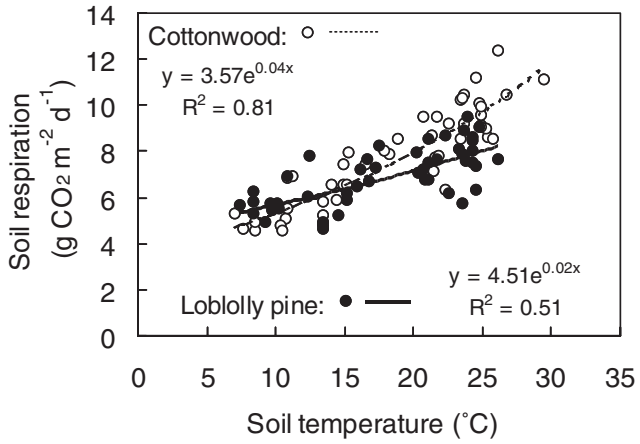

Figure 3—Relationship between soil respiration and soil temperature in 7-year-old cottonwood and loblolly pine plantations in northwest Florida.

Microbial Biomass C

There was no difference in soil microbial biomass C between cottonwood and loblolly pine stands (table 1); however, N fertilization negatively affected soil microbial biomass C (P = 0.048) in both species (figs. 1E, 1F). Similar results have been reported from other long-term fertilization trials (Fisk and Fahey 2001, Scott and others 1998). For example, Fisk and Fahey (2001) reported that microbial biomass C was significantly reduced by 8 years of continued N fertilization in a temperate hardwood forest. In contrast, shorter-term N fertilization has been shown to increase microbial biomass (Gallardo and Schlesinger 1994, Hart and Stark 1997). The immediate increase in microbial biomass following N additions suggests that N could be limiting in the soil. However, there is no obvious explanation for the decrease in microbial biomass over longer periods of treatment (Fisk and Fahey 2001). Although soil acidification and subsequent reduction in microbial biomass C could be suspected, we did not observe this for either species.

CONCLUSIONS

Soil respiration decreased significantly along an increasing soil N gradient in cottonwood; however, it remained unchanged in loblolly pine. The speculation that fertilization might lower soil C due partially to increased soil respiration was found untenable in our experiment. Contrary to our expectation and some published reports, fine root production exhibited no significant differences among treatments in both species. There was a trend of decreasing fine root production in cottonwood and increasing production in loblolly pine along the increasing soil N gradient, which may become more pronounced in the future as stands get older. Averaged across all treatments, loblolly pine had 35 percent lower fine root production than cottonwood. Microbial biomass decreased along the increasing N gradient in both species and was correlated strongly to soil organic matter and pH. In general, our results suggest that long-term N fertilization can modify belowground soil processes in both hardwood and coniferous stands, but not always in identical ways.

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REAPPLICATION OF SILVICULTURAL TREATMENTS IMPACTS PHENOLOGY AND PHOTOSYNTHETIC GAS EXCHANGE OF LOBLOLLY PINE

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Abstract—A loblolly pine (*Pinus taeda* L.) plantation, established in 1981, was thinned and fertilized in 1988. Thinning and fertilization treatments were applied again in early 1995. The morphology of current flushes and needles were measured between March and October in 1995 through 1997. Physiological responses were monitored in the upper and lower crowns. Needle-fall was collected biweekly, and annual needle biomass was estimated. Although refertilization had little impact on needle-level physiology, it shifted bud burst 1 week earlier and significantly enhanced flush and needle growth. The fertilized trees produced more leaf area per shoot than the unfertilized trees. Refertilization increased tree-level and plot-level annual needle-fall biomass production. Rethinning increased leaf area per fascicle and annual needle-fall biomass per tree. As light level and crown exposure were increased after rethinning, rates of photosynthesis and transpiration of lower crown foliage on the thinned plots rose considerably, but daytime needle water potential remained unaffected.

INTRODUCTION

Forest growth and productivity depend, in part, on the availability of site resources. Nutrient deficiency and drought significantly reduce aboveground and belowground productivity of conifers (Albaugh and others 1998, Sword and others 1998, Teskey and others 1994). Light availability affects canopy structure, branch physiology, and tree growth (Ginn and others 1991, Sheriff 1996, Tang and others 1999). Forest management activities such as thinning and fertilization increase site quality and stand production (Jokela and Martin 2000). Growth responses to silvicultural treatments have been shown to persist for several years. For instance, Brix (1983) found that nitrogen (N) fertilization and thinning increased annual growth of Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] trees for 3 to 5 years. At a Louisiana site, fertilization with N and phosphorous (P) stimulated stem volume increment of loblolly pine (*Pinus taeda* L.) saplings for 4 years (Haywood 1994).

In general, the effects of forest management on relationships between site quality and growth response are not well understood. Studies of tree responses to repeated cultural practices are needed to understand when to implement intensive management for maximizing the productivity that is associated with canopy processes and carbon dynamics (Jokela and Martin 2000, Leverenz and Hinckley 1990, Maier and others 2002, Samuelson and others 2001). This study is part of a long-term project that assesses the impacts of silvicultural manipulations on loblolly pine productivity. The objectives of the study were to (1) quantify flush and foliage growth of 14- to 16-year-old trees 3 years after the second thinning and fertilization, and (2) evaluate physiological performance under different treatment conditions.

MATERIALS AND METHODS

Study Site

The study was conducted on the U.S. Department of Agriculture, Forest Service, Southern Research Station, Palustris Experimental Forest in Louisiana, where the soil was moderately well drained Beauregard silt loam (fine-silty, siliceous, thermic, Plinthaquic Paleudults). In 1981, the plantation was established by planting 3-month-old seedlings at 1.8 x 1.8 m spacing. A factorial combination of two levels each of thinning (thinned or unthinned) and fertilizing (fertilized or unfertilized) treatments, replicated 3 times, was applied to 12 plots (0.57 ha each) in late 1988. On the thinned plots, a row thinning was done with 721 trees ha^{-1} remaining. The unthinned plots had nearly 2,900 trees ha^{-1}. In early 1989, diammonium phosphate (134 kg N and 150 kg P ha^{-1}) was broadcast on the fertilized plots. Thinning and fertilization treatments were reapplied in early 1995. The previously thinned plots were cut again to approximately 510 trees ha^{-1} (16 m^2 ha^{-1}) representing 30 percent of maximum stand density index for loblolly pine grown on Gulf coastal sites (Dean and Baldwin 1993). Stand density of the unthinned plots was 2,860 trees ha^{-1} (42 m^2 ha^{-1}). Urea, triple super phosphate and potash (200 kg N, 50 kg P, and 50 kg K ha^{-1}) were broadcast on the plots that had been fertilized before. Understory hardwoods and shrubs on the plots were removed with a rotary mower, and glyphosate herbicide was sprayed to control weed competition.

Field Measurements

From 1995 to 1997, flush and needle growth were measured in the upper and lower crown of two treatment replications (four plots per replication). At each crown position, four first-order branches each on the south and north side of tree crowns (16 branches per plot) were randomly selected in February. These branches were situated in four to six interior trees on each plot. On the

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

branch, one first flush per terminal or adjacent shoot was sampled and flush shoot length was recorded biweekly from March to October. Three needle fascicles on the sample flush were marked randomly and their needle length (from the tip to the edge of the leaf sheath) was measured biweekly between April and October. Similar measurements were made on the subsequent flushes (second and third) of the same sample shoot as trees grew multiple flushes throughout the growing season. Additionally, needle fascicle density (fascicles per cm of the foliated flush shoot) was determined in November 1997.

Each October, two fascicles per sample flush shoot were randomly chosen in the upper and lower crown of six trees per plot, and totally 192 fascicles were removed from the eight plots and examined in the laboratory. Each fascicle was cut at the edge of the leaf sheath. Needle length and volume per fascicle were measured. Leaf surface area per fascicle was estimated from needle length and volume (Johnson 1984). Leaf area per flush was calculated as the product of flush length, fascicle density, and leaf area per fascicle. Number of flushes per shoot was calculated by adding numbers of multiple flushes (first, second, and so forth) that grew on each sample shoot throughout the growing season. Annual flush shoot length was the sum of the length of the measured flushes on the sample shoot, and leaf area per shoot was the sum of the leaf area of the measured flushes on the sample shoot.

Four litter traps (0.92 m^2 each) were randomly installed inside each of the eight plots. Needle-fall was collected biweekly from 1995 to 1998, oven-dried to a constant mass, weighed, and expressed on a plot-area basis. Annual needle-fall biomass per plot was calculated for a phenological year by adding needle dry mass from April to March. Annual foliage biomass per tree was determined by dividing annual needle-fall biomass per plot by number of trees per plot.

On sunny days, needle gas exchange was measured in the upper and lower crown of the interior trees in two replications (eight plots) where shoot and needle morphology were also measured. Gas exchange measurements were taken nearly twice each month from June to October in 1995. The same measurements were made between April and October in 1996 and 1997. During each period, we randomly sampled four plots in one replication on the first day and the other four plots the next day. On a sampling day, three fascicles each from the upper and lower crown (six fascicles per plot) were detached before daylight and their predawn leaf water potentials (Ψ_{pd}) were determined with a pressure chamber (PMS Instrument Co., Corvallis, OR). Photosynthetic measurements were performed between 0930 and 1130 h, using a LI-6200 infrared gas analyzer (closed system) equipped with a 250-mL leaf chamber (Li-Cor, Inc., Lincoln, NE). At each crown position, three branches, each from the south side of three different trees, were selected. Two fully-expanded needle fascicles in the mid-section of the terminal or nearby lateral shoot were placed in the leaf chamber and their net CO_2 exchange (P_n), transpiration (E), and stomatal conductance to water vapor (g_w) were recorded *in situ* under the natural environment. Photosynthetic photon flux density (PPFD), air temperature (T_a), and vapor pressure deficit (VPD) were monitored with the gas analyzer. Needle water potentials (Ψ_{md}) of the sample fascicles were determined using the pressure chamber after each P_n measurement.

Volumetric soil water content (SWC) at the 15-cm depth was measured nearly twice a month at three locations in the interior of each plot with a time domain reflectometer (Soil Moisture Equipment Corp., Santa Barbara, CA).

Statistical Analyses

To test the effects of repeated thinning and fertilization on flush and needle growth, morphological data of each October were analyzed using the analysis of variance for a complete random split-plot design. Thinning and fertilization were considered as the main treatments, sampling year as the subplot and crown position as the sub-subplot. Similar analysis was done on physiology, soil water, and needle-fall data. Main and interactive effects on flush shoot growth, needle-fall biomass production and gas exchange were considered statistically significant at $P \leq 0.10$. All data analyses were conducted with the SAS software package (SAS Institute Inc., Cary, NC).

RESULTS

Shoot and Needle Phenology

Bud burst occurred in the first week of March. By mid-March, 64 and 47 percent of the sample shoots on both fertilized and unfertilized plots, respectively, had bud burst. First flushes expanded rapidly in the early growing season (figs. 1A to 1C). Overall, first-flush shoot elongation averaged 4.0 cm $week^{-1}$ in March, declined to 1.6 cm $week^{-1}$ in April and terminated by the end of May. First-flush needles began elongating in late March and averaged 1.1 cm $week^{-1}$ in May and June. Second flushes grew from May to August, and their needles continued growing through September. The third flushes were observed only in the upper crown and grew between midJuly and October.

Flush and needle morphology positively responded to fertilization (table 1). Over all 3 years, thinning treatments and crown levels, mean shoot length and leaf area per first flush were significantly greater on the fertilized plots than on the unfertilized plots (table 2). Mean shoot length and leaf area per second flush were also greater for the fertilized plots as compared with the unfertilized plots. There was a significant interaction between fertilization and crown position on annual production of multiple flushes. In addition to the first flush, both fertilized and unfertilized trees grew one second and one third flush per shoot in the upper crown. In the lower crown of the fertilized plots, however, one second flush was found for all sample shoots and one third flush for 67 percent of the sample shoots. In contrast, only 8 percent of the sample shoots in the lower crown of the unfertilized trees had one second flush, and no third flush was found in the same crown level. First-flush and second-flush fascicles had significantly greater needle length and leaf area per fascicle for the fertilized trees than for the unfertilized trees (table 2). Annual flush shoot length was increased consistently for the 3 years after refertilization (fig. 2A). Relative to the unfertilized plots, flush shoots of the fertilized trees possessed significantly more leaf area per shoot in 1995 and 1996 (fig. 2B). Moreover, the

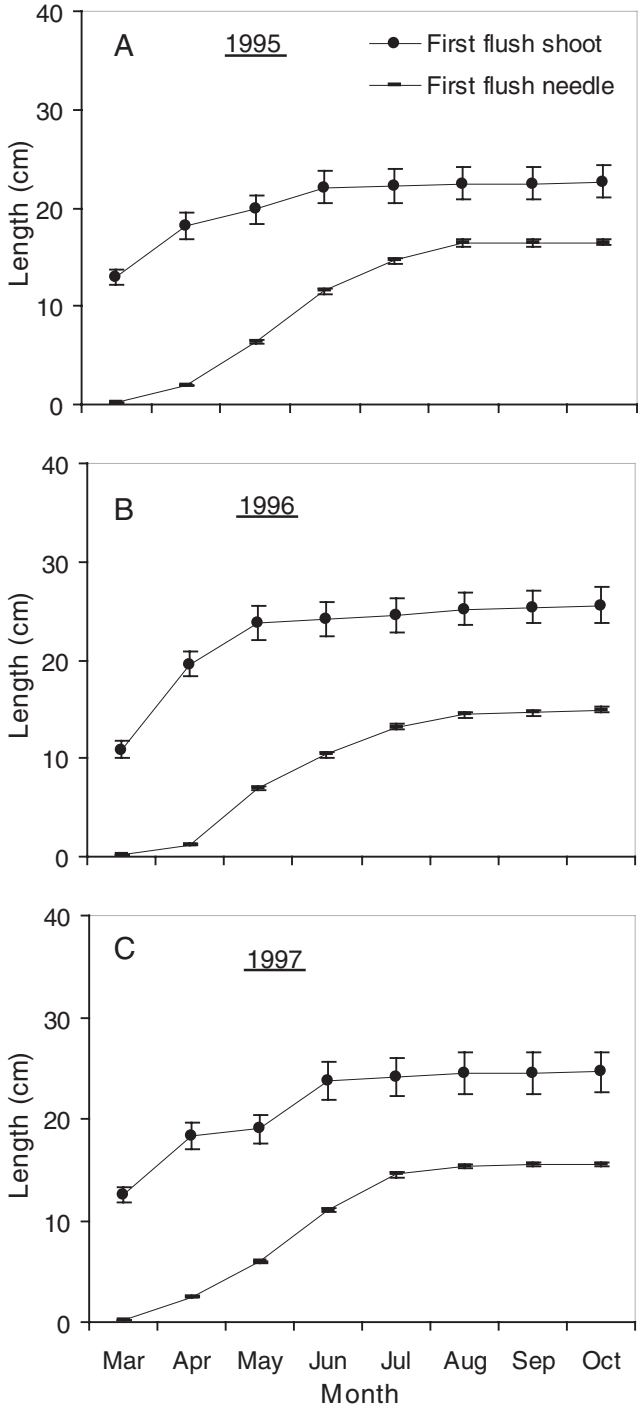

Figure 1—Mean length of first flushes and first-flush needles of 14- to 16-year-old loblolly pine trees 3 years after reapplication of thinning and fertilization. Each mean is the average of biweekly measurements across rethinning and refertilization treatments and crown positions.

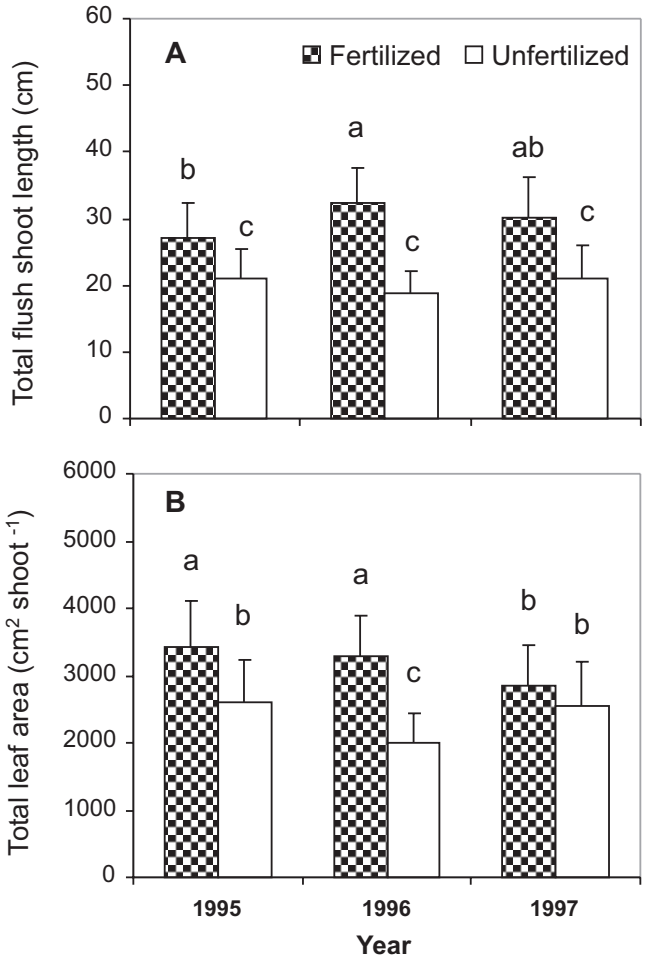

Figure 2—Mean annual flush shoot length and leaf area per shoot of 14- to 16-year-old loblolly pine trees 3 years after refertilization. Each mean is the average of biweekly measurements across rethinning treatments and crown positions. Bars followed by the same letters do not differ significantly at $P \leq 0.10$.

fertilized plots had more annual needle-fall biomass per tree and per plot than the unfertilized plots during the 3-year period (figs. 3A and 3B).

Rethinning significantly increased first-flush fascicle size and leaf area in the upper and lower crown (table 1). Mean needle length and leaf area of the first-flush fascicles were greater on the thinned plots than on the unthinned plots. A significant interaction between thinning and crown position indicated that shoot length and leaf area of upper-crown first flushes were larger on the unthinned plots compared to the thinned plots. Annual flush shoot length positively responded to rethinning, with more flushes per shoot in the lower crown of the thinned trees than those in the same crown level of the unthinned trees. Annual shoot length was 39, 35, 16, and 11 cm for the unthinned-upper, thinned-upper, thinned-lower, and unthinned-lower crown combinations, respectively. Leaf area per shoot was 4,691, 3,838, 1,459, and 1,157 cm^2 for the thinning-by-crown position combinations. Annual foliage production was enhanced by stand density reduction. Needle-fall biomass per tree on the unthinned plots remained identical over the 3 years after rethinning (fig. 3C). However, the thinned trees significantly increased needle-fall production each year. In 1997, needle-fall biomass per tree was 221 percent more on the thinned plots than on the unthinned plots. However, annual needle-fall biomass per plot was lower for the thinned plots (fig. 3D) relative to the unthinned plots because of fewer trees remaining after rethinning.

Table 1—Probability of F-test for the effects of repeated thinning and fertilization treatments and crown position on October flush and needle characteristics of 14- to 16-year-old loblolly pine trees 3 years after treatment in Louisiana

Source of variation	df	FFLG	FFLA	FFNL	FFNA	SFLG	SFLA	SFNL	SFNA	MFPS	FSLG	FSNA
T	1	0.8619	0.3318	0.0426	0.0095	0.5563	0.5843	0.6865	0.3938	0.2508	0.8458	0.3066
F	1	0.0118	0.0407	0.0035	0.0013	0.0219	0.0752	0.0246	0.0160	0.0352	0.0057	0.0279
T x F	1	0.2938	0.3866	0.6036	0.1335	0.1041	0.2368	0.2634	0.1616	0.0890	0.1130	0.7219
Error a	4											
SY	2	0.1621	0.1612	0.0034	0.0001	0.1122	0.0681	0.0030	0.0016	0.3628	0.6141	0.2388
SY x T	2	0.3771	0.5044	0.1227	0.0910	0.8307	0.6948	0.6320	0.5645	0.3628	0.4867	0.4321
SY x F	2	0.1017	0.3399	0.0186	0.0016	0.5379	0.1336	0.0970	0.0441	0.6927	0.1738	0.1427
SY x T x F	2	0.1828	0.3903	0.2692	0.2373	0.1886	0.2095	0.7046	0.6682	0.6927	0.1891	0.2291
Error b	8											
C	1	0.0001	0.0001	0.6909	0.0001	0.0357	0.0279	0.6709	0.8640	0.0875	0.0071	0.0061
C x F	1	0.0038	0.3749	0.2531	0.0322	0.5615	0.9673	0.6793	0.5588	0.0010	0.0306	0.3980
C x T X F	1	0.5071	0.6392	0.1222	0.2069	0.4421	0.4498	—	—	0.0092	0.9079	0.9280
Error c	20											

T = thinning; F = fertilization; SY = sampling year; C = crown; df = degree of freedom; FFLG = first-flush length; FFLA = leaf area per first flush; FFNL = first-flush needle length; FFNA = leaf area per first-flush fascicle; SFLG = second-flush length; SFLA = leaf area per second flush; SFNL = second-flush needle length; SFNA = leaf area per second-flush fascicle; MFPS = numbers of multiple flushes per shoot; FSLG = annual flush shoot length; FSNA = leaf area per flush shoot.

Table 2—Mean values of the October flush and needle characteristics of 14- to 16-year-old loblolly pine trees in response to repeated thinning and fertilization treatments and crown positions 3 years after treatment in Louisiana

Measured variable	T	UT	F	UF	UC	LC
First flush shoot						
Flush length (*cm*)	18.2 a	18.5 a	21.4 a	15.3 b	26.5 a	10.3 b
Leaf area per flush (cm^2)	2,162 a	2,370 a	2,548 a	1,985 b	3,340 a	1,193
Fascicle needle length (*cm*)	16.6 a	15.1 b	17.4 a	14.3 b	15.9 a	15.8 a
Leaf area per fascicle (cm^2)	16.2 a	14.0 b	16.9 a	13.3 b	15.9 a	14.2 b
Second flush shoot						
Flush length (*cm*)	5.6 a	5.1 a	6.7 a	4.1 b	8.6 a	2.2 b
Leaf area per flush (cm^2)	478 a	526 a	601 a	404 b	889 a	115 b
Fascicle needle length (*cm*)	12.5 a	12.4 a	13.5 a	10.7 b	12.6 a	12.0 b
Leaf area per fascicle (cm^2)	12.5 a	12.4 a	13.6 a	10.7 b	12.7 a	11.3 b
Annual flush shoot						
Multiple flushes per shoot	2.8 a	2.6 a	2.8 a	2.5 b	3.0 a	2.3 b
Flush shoot length (*cm*)	25.3 a	24.9 a	29.9 a	20.3 b	37.1 a	13.0 b
Leaf area per shoot (cm^2)	2,648 a	2,924 a	3,184 a	2,389 b	4,265 a	1,308 b

T = thinned plot; UT = unthinned plot; F = fertilized plot; UF = unfertilized plot; UC = upper crown; LC = lower crown.
Means followed by the same letters for each variable within thinning or fertilization treatments or crown positions do not differ significantly at $P \leq 0.10$.

Needle-level Physiology

Photosynthetic gas exchange of foliage did not vary significantly with year (table 3). Across all treatments and crown levels, mean P_n, based on a needle surface area, was 3.5 μmol m^{-2} s^{-1}. Mean g_w and E were significantly higher in 1995 than in 1997. Differences in g_w and E were associated with a significant difference in Ψ_{pd} and SWC between the 2 years. Mean Ψ_{pd} and SWC were -0.56 MPa and 25.9 percent by volume, respectively, in 1995 and -0.72 MPa and 21.5 percent in 1997. Mean Ψ_{md} in late morning was significantly different among the years with more negative values (-1.23 and -1.28 MPa) in 1995 and 1997 than the value (-1.09 MPa) in 1996.

Large variation in light intensity was found vertically within the canopy of the unthinned plot (fig. 4A). Low light limited

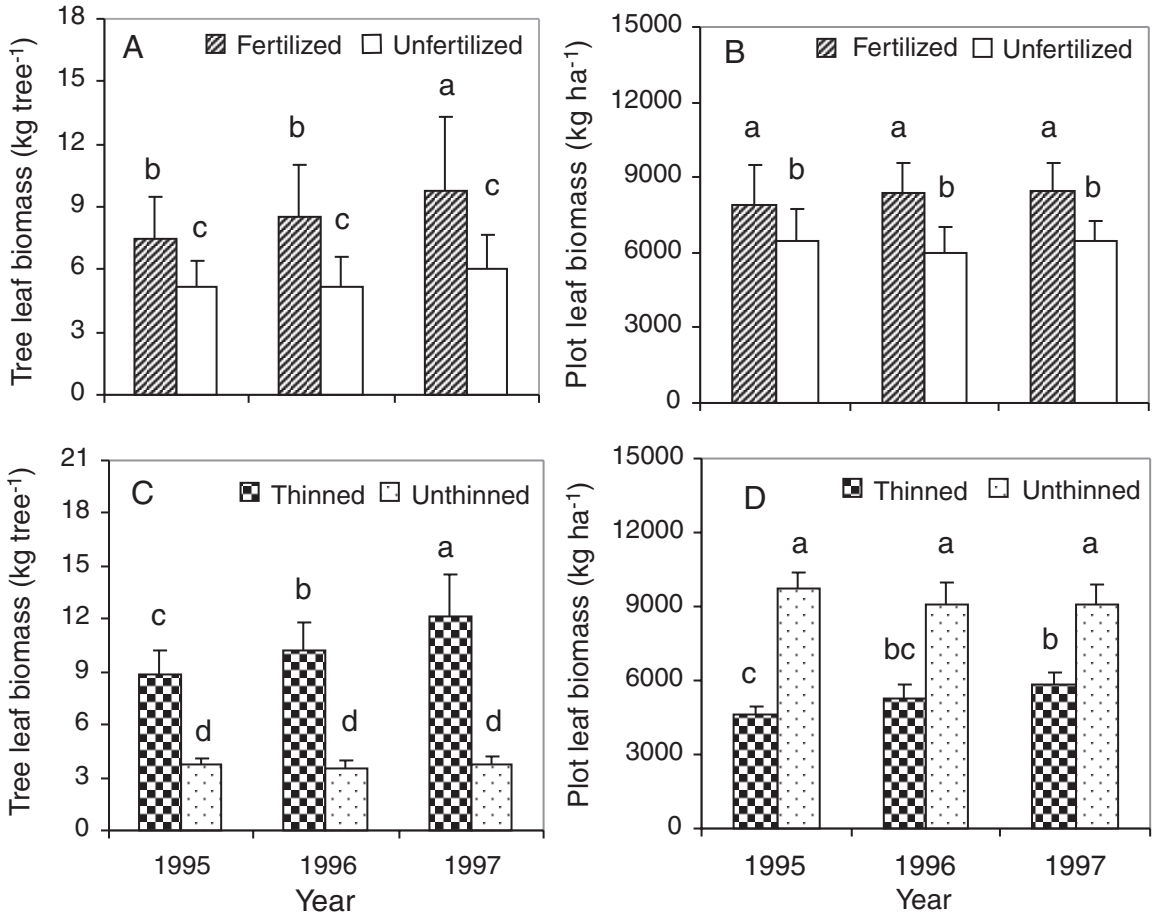

Figure 3—Mean annual needle-fall biomass per tree and per plot 3 years after refertilization and rethinning. Bars followed by the same letters do not differ significantly at $P \leq 0.10$.

Table 3—Probability of F-test for the effects of repeated thinning and fertilization treatments and crown position on the physiological variables of 14- to 16-year-old loblolly pine trees 3 years after treatment in Louisiana

Source of variation	df	P_n	g_w	E	Ψ_{md}	Ψ_{pd}
T	1	0.0253	0.2112	0.0688	0.1206	0.0597
F	1	0.2320	0.4722	0.7108	0.0454	0.0121
T x F	1	0.5577	0.8266	0.9428	0.4988	0.3054
Error a	4					
SY	2	0.1909	0.0001	0.0071	0.0012	0.0001
SY x T	2	0.1219	0.5342	0.6074	0.9554	0.4054
SY x F	2	0.6700	0.9580	0.6792	0.3976	0.3617
SY x T x F	2	0.6454	0.6186	0.5921	0.9571	0.5858
Error b	8					
C	1	0.0001	0.0005	0.0004	0.0003	0.2951
C x T	1	0.0045	0.0055	0.0102	0.0333	0.3750
C x F	1	0.4497	0.4000	0.5766	0.9849	0.6269
C x T x F	1	0.2150	0.4080	0.2906	0.4743	0.6313
Error c	276					

df = degree of freedom; P_n = photosynthesis; g_w = stomatal conductance to water vapor; E = transpiration; Ψ_{md} = daytime needle water potential; Ψ_{pd} = predawn needle water potential; T = thinning; F = fertilization; SY = sampling year.

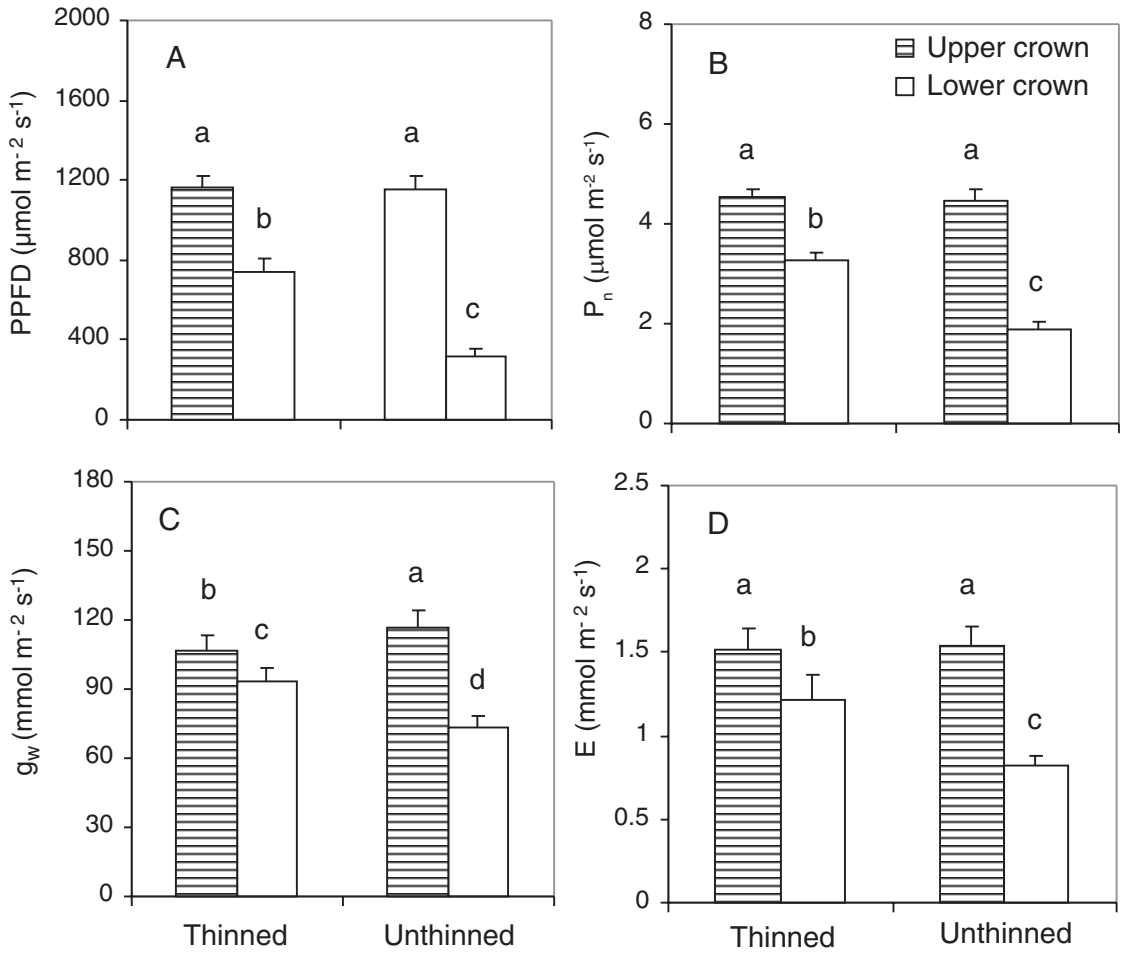

Figure 4—Mean photosynthetic photon flux density (PPFD), photosynthesis (P_n), stomatal conductance (g_w) and transpiration (E) of 14- to 16-year-old loblolly pine trees 3 years after rethinning. Bars followed by the same letters do not differ significantly at $P \leq 0.10$.

photosynthetic activity of lower crown foliage of the unthinned trees. Rethinning significantly increased light penetration and crown exposure, and, therefore, P_n and E of the thinned trees (tables 3 and 4). Across the 3 years, mean PPFD in the lower crown rose 133 percent on the thinned plots in comparison with the unthinned plots. Lower-crown needle P_n on the thinned plots increased 73 percent (fig. 4B). The thinned trees also had higher g_w and E rates (figs. 4C and 4D) and more negative Ψ_{md} in the lower-crown needles. Mean SWC and Ψ_{pd} were slightly and significantly higher on the thinned plots than on the unthinned plots.

Table 4—Mean values of the physiological characteristics of 14- to 16-year-old loblolly pine trees in response to repeated thinning and fertilization and crown positions 3 years after treatment in Louisiana

Measured variable	T	UT	F	UF	UC	LC
P_n (mmol m^{-2} s^{-1})	3.88 a	3.20 b	3.68 a	3.40 a	4.53 a	2.56 b
g_w (mmol m^{-2} s^{-1})	101 a	96 a	97 a	100 a	113 a	83 b
E (mmol m^{-2} s^{-1})	1.37 a	1.20 b	1.29 a	1.27 a	1.55 a	1.02 b
Ψ_{md} (MPa)	-1.22 a	-1.17 a	-1.16 a	-1.24 b	-1.29 b	-1.11 a
Ψ_{pd} (MPa)	-0.61 a	-0.64 b	-0.60 a	-0.65 b	-0.63 a	-0.62 a

T = thinned; UT = unthinned; F = fertilized; UF = unfertilized; UC = upper crown; LC = lower crown; P_n = photosynthesis; g_w = stomatal conductance to water vapor; E = transpiration; Ψ_{md} = daytime needle water potential; Ψ_{pd} = predawn needle water potential. Means followed by the same letters within thinning or fertilization treatments or crown positions do not differ significantly at $P \leq 0.10$.

Refertilization did not have a significant effect on needle P_n, g_w, and E (tables 3 and 4). Mean Ψ_{pd} and $_{md}$ were more negative on the unfertilized plots than on the fertilized plots, but SWC was unaffected by refertilization. Statistically, there was no two-way or three-way interaction among thinning, fertilization and crown position on the physiological attributes.

DISCUSSION

Yu and others (1999) found that maximum increases in annual ring width and stem volume occurred in the third year following the first thinning at our study site. In 1995, 6 years after treatment, however, annual volume growth in response to thinning already decreased to the same level before the first thinning. Prior to rethinning, we observed that crown closure began to take place on the thinned plots. Photosynthetic photon flux density (PPFD) and P_n in the lower crown were only 24 and 28 percent higher, respectively, on the thinned plots compared to the unthinned plots (Tang and others 1999). At that time, differences in shoot and leaf area growth no longer existed between thinned and unthinned plots (Yu and others, in press).

The most important thinning-related change found in this study was the increase in solar radiation on the thinned plots. Over 3 consecutive years after rethinning, PPFD and P_n in the lower crown of the thinned trees rose 133 and 73 percent, respectively. The magnitude of increases in PPFD and P_n in response to rethinning was similar to the magnitude reported by Ginn and others (1991) and Peterson and others (1997) who examined the thinning effects on gas exchange rates of juvenile loblolly pine in Virginia. Our data show that P_n responses to repeated thinning can attain the level following first thinning.

We also found that rethinning stimulated leaf area per fascicle in the lower crown and needle-fall biomass production per tree. Positive responses in both leaf area growth and photosynthesis per unit leaf area could result in a substantial increase in whole-tree carbon uptake. With the advantage of more carbon uptake, thinned-plot trees may have maintained more optimal stem volume growth over the age of the stand than if only first thinning was done (Brix 1983, Sheriff 1996, Yu and others 1999). Commercial thinning of loblolly pine stands in the South is repeated as often as every 10 years for enhancing merchantable saw timber production (Schultz 1997). However, our study suggested that subsequent thinning may be needed sooner than 10 years to increase net photosynthesis rate, leaf area growth and foliage production for maximum volume increment.

Positive P_n responses to fertilization appeared to be inconsistent. On a site low in N and P, for instance, Sheriff and others (1986) found that P, but not N, addition was positively correlated with P_n rates of 7-year-old radiata pine (*Pinus radiata* Don). Thompson and Wheeler (1992) reported a positive relationship between foliar N concentration and carbon uptake of 14-year-old radiata pine. But this relationship was only evident outside the growing season when g_w was less than 75 mmol m^{-2} per second. Teskey and others (1994) observed that N fertilization together with other micro- and macro-nutrients did not alter P_n rates of 23-year-old slash pine (*Pinus elliottii* Engelm.). However, the supply with micro- and macro-nutrients increased light-saturated P_n of 9-year-old loblolly pine on a nutrient-poor soil in North Carolina 2 years after treatment (Murthy and others 1996). Four years later, at the same site, Maier and others (2002) found little fertilization effect on gas exchange. At our site, N and P levels were inherently low in the Beauregard silt loam soil (Tiarks and Haywood 1986). Initial N and P fertilization improved soil fertility and increased volume growth for 4 post-treatment years (Yu and others 1999). For this study, we hypothesized that a fertilization-induced increase in tree growth was partly caused by increases in carbon uptake rates. However, P_n was not different between both fertilized and unfertilized plots. Similarly, Zhang and others (1997) evaluated 4-year-old loblolly pine trees on a southeastern Oklahoma site and revealed no impact of N fertilization on photosynthetic rates. Their results suggest that N-induced increases in foliar chlorophyll concentrations and P_n rates of shaded foliage may only be apparent on sites where leaf chlorophyll and N levels are extremely low. Consistent with the suggestion of Zhang and others (1997), several other researchers have found that a more than 30 percent increase in foliar N concentration of pines grown on nutrient-poor sites was related to an increase in carbon fixation (Beets and Whitehead 1996, Fife and Nambiar 1997).

Low nutrient availability at our site reduced foliage production on the unfertilized plots (Sword and others 1998). Reapplication of N-P-K fertilizers persistently enhanced flush shoot and needle growth. We observed that the fertilized trees annually produced more flushes per shoot, longer flush shoots and greater leaf area per shoot. These findings agree with the measurements reported by Maier and others (2002), who found a 38 percent increase in branch leaf area of 13 year old loblolly pine 5 years after fertilization on a nutrient-poor site in North Carolina. We also observed that tree-level and plot-level needle-fall biomass production was increased by refertilization during the study. The advantage in flush growth and foliage production on the fertilized plots could be one of the major factors for increasing intercepted radiation within the canopy and tree productivity (Albaugh and others 1998, Leverenz and Hinckley 1990, Samuelson and others 2001). Continued assessment of the effects of site factors and cultural practices on canopy physiology and growth response is necessary for a better understanding of the productivity of southern pines in relation to forest management and the changing environment.

ACKNOWLEDGMENTS

Research support was provided through the project "Assessment of Global Change/Cultural Practice Effects on Loblolly Pine Eco-Physiological Responses: Responses to a Secon Application of Thinning and Fertilization Treatments, Phase II" dated October 1, 1995 through September 30, 1997 of Cooperative Agreement 30-96-017. This study was partially funded by the U.S. Department of Agriculture, Forest Service, Southern Global Change Program.

The authors thank Jim Scarborough, Dan Andries, and Eric Keuhler for their assistance in tower system maintenance and data collections. The authors also gratefully appreciate Suresh Guddanti, Jian Sun, and Karen Velupillai for their contribution.

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LONG-TERM ROOT GROWTH RESPONSE TO THINNING, FERTILIZATION, AND WATER DEFICIT IN PLANTATION LOBLOLLY PINE

M.A. Sword-Sayer and Z. Tang[1]

Abstract—High water deficits limit the new root growth of loblolly pine (*Pinus taeda* L.), potentially reducing soil resource availability and stand growth. We evaluated new root growth and stand production in response to thinning and fertilization in loblolly pine over a 6-year period that consisted of 3 years of low water deficit followed by 3 years of high water deficit. We found that new root growth exhibited a distinct seasonal pattern, with the timing of maximum root growth affected by water deficit. The magnitude of root growth was affected by both water deficit and thinning. For the 3-year period of high water deficit, we observed an inverse relationship between stemwood production and root growth among the treatment combinations. We hypothesize that by the third year of high water deficit, absorbing roots had migrated deeper into the soil profile; as a result, deep soil water became available for the high rates of stand production observed.

INTRODUCTION

Past research has shown that new loblolly pine (*Pinus taeda* L.) root growth is modal, with a maximum in midspring through midsummer (Farrish 1991, Sword and others 1998). Low soil water potential and high soil strength reduce root growth (Kaufmann 1968, Torreano and Morris 1998, Wraith and Wright 1998). Because these soil properties become more adverse as soil dries, the depletion of plant-available water inhibits new root growth. Loblolly pine root growth peaks during periods of high evaporative demand (Allen and others 1990), which suggests that water availability may be closely related to the production of new loblolly pine roots.

New root growth is needed for the absorption of soil resources that maintain tree physiology and growth. The effects of water deficit on new root growth, therefore, could limit stand production. Forest management activities such as thinning and fertilization may also interact with water deficit to affect new root growth. The objectives of this study were to summarize the new root growth of plantation loblolly pine over a 6-year period that included a period of high annual water deficit, and to assess new loblolly pine root growth responses to thinning and fertilization during this same time period. Choosing current annual stemwood biomass increment (CAI) as a variable representative of stand production, we evaluated the relationship between CAI and new root growth over the 6-year period.

MATERIALS AND METHODS

Study Establishment

The study is located in Rapides Parish, LA, on the Palustris Experimental Forest. The soil is a moderately well drained, very gently sloping Beauregard silt loam (fine-silty, siliceous, thermic, Plinthaquic Paleudults) (Kerr and others 1980). Plant available water to a 1-m depth is 183 mm. Average annual rainfall is 156 cm, and average daily air temperature in summer and winter are 27.4 ˚C and 11.4 ˚C, respectively. We determined monthly and annual water balances for the 6-year period between 1993 and 1998 (Thornthwaite and Mather 1955). Rainfall was monitored electronically in an open field adjacent to the study area. Air temperature was obtained from the Louisiana State University Agricultural Center's Dean Lee Research Station located 37 km east of the study.

In May 1981, container-grown loblolly pine seedlings from a woods-run source were planted by U.S. Department of Agriculture Forest Service personnel in the experimental forest at 1.8 by 1.8 m. In 1988, 12 treatment plots (0.06 ha), 13 rows of 13 trees each, were established, and the interior 49 trees were delineated as measurement plots (0.016 ha). Woody vegetation was mowed from the plots, and 2 percent aqueous glyphosate was applied as needed to control grass and herbaceous plants during the study.

In 1988, two levels of thinning (none—2,990 trees/ha, thinned—749 trees/ha), and in 1989, two levels of broadcast fertilization with diammonium phosphate [none and 135 kg nitrogen (N) plus 150 kg phosphorus (P) per ha], were randomly applied to the treatment plots in a factorial design (Haywood 1994). In 1995, the previously thinned plots were rethinned from below so that mean basal area was reduced from 18.2 m^2/ha to 15.4 m^2/ha, and the fertilized plots were refertilized with a broadcast application of urea, monocalcium phosphate, and potash [200 kg N, 50 kg P, and 50 kg potassium (K) per ha]. In 1993, we chose two replications as blocks for intensive root growth measurements. Blocks were chosen by the influence of topography on soil drainage.

Measurements

During the dormant season of every year between 1993 and 1998, we measured total tree height and diameter at breast height (d.b.h.). Inside-bark dry stem mass per tree was predicted by an equation from Baldwin and Feduccia (1987). We calculated CAI for each measurement plot and year as the difference between the megagrams (Mg) of

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

standing stem mass at the beginning of the growing season and the Mg of standing stem mass at the end of the growing season plus the Mg of stem mass that was lost during the year from thinning or mortality. Values of CAI are expressed as Mg/ha/year.

In 1993, we installed three Plexiglas rhizotrons (3 by 35.4 by 76 cm) vertically in the soil at three random locations in each measurement plot (Sword and others 1998). Between 1994 and 1998, two more Plexiglas rhizotrons were installed. Rhizotrons were relocated in January and February of each year. At 2- to 5-week intervals beginning in April, the elongation of new roots $\geq$ 5 mm in the 0- to 30-cm depth of rhizotrons was traced with permanent markers onto acetate sheets (21.6 by 30 cm) attached to either side of rhizotrons.

We recorded observations cumulatively. A computer image file of each acetate sheet was created by measurement interval, and the length of lines contained in each image file was quantified using GSROOT software (PP Systems, Inc., Bradford, MA). Net root elongation was calculated by subtraction. Net root initiation at the 0- to 5-cm, 5- to 15-cm, and 15- to 30-cm depths was quantified by counting the number of newly emerged roots $\geq$ 5 mm in rhizotrons during each measurement interval. Root elongation rate was expressed as mm/dm^2/day, root initiation rate was expressed as number/dm^2/day, and mean monthly root elongation and initiation rates were calculated. Annual peak root elongation and initiation were calculated as the average of root elongation and initiation rates between May and October. Amounts of root elongation and initiation that accumulated in rhizotrons since June were calculated for each month between June and October. Cumulative root elongation and initiation were expressed as mm/dm^2 and number/dm^2, respectively.

Statistical Analyses

Monthly root elongation and initiation rates were transformed to square root values to insure that the data were normally distributed. Data were analyzed by analysis of variance using a randomized complete block, split plot design with two blocks. Whole plots were levels of thinning and fertilization, and subplots were month of year. Peak root elongation and initiation were analyzed by analysis of variance using a randomized complete block, split plot design with two blocks. Whole plots were levels of thinning and fertilization, and subplots were years. Values of CAI between 1993 and 1998 were analyzed by analysis of variance using a randomized complete block design with two blocks. Treatments were levels of thinning and fertilization. Main and interaction effects were considered significant at $P \leq 0.05$ unless otherwise noted, and significantly different treatment means were compared with the least significant difference test at $P \leq 0.05$.

Linear relationships between cumulative root elongation and initiation between June and October and annual water deficit, and cumulative root elongation and initiation between June and October and CAI were evaluated by ordinary least squares regression. The slopes of the regression equations were considered significant at $P \leq 0.05$.

RESULTS

Between 1993 and 1998, annual water deficit ranged between 91 mm in 1995 and 343 mm in 1998. Mean annual water deficit in 1996 through 1998 was 1.2 times higher than that in 1993 through 1995. Root elongation and initiation rates differed significantly by month of year (tables 1 and 2). Peak rates of root elongation at the 0- to 30-cm depth occurred during May through July in 1993–97 and August through October in 1998 (fig. 1). Peak rates of root initiation at the 0- to 5-cm, 5- to 15-cm, and 15- to 30-cm depths occurred during May through July in 1993-96, June through August in 1997, and August through October in 1998, respectively.

Root elongation rate at the 0- to 30-cm depth and root initiation rates at the 0- to 5-cm and 15- to 30-cm depths were significantly affected by thinning (tables 1 and 2), with greater rates of root growth on the thinned plots than on the unthinned plots. For root initiation rate at the 0- to 5-cm depth, the significant interaction between month of year

Table 1—Analysis of variance of mean monthly loblolly pine root elongation rate (mm per dm^2 per day) at the 0- to 30-cm depth in response to thinning and fertilization in a loblolly pine plantation in central Louisiana, 1993 to 1998

Source of variation	df	SS	MS	F-value	Pr > F
Block	1	0.0159	0.0159	0.16	0.6954
Month of year	53	118.16	2.2295	21.8	0.0001
Error a	53		0.1022		
Thinning	1	4.2119	4.2119	41.9	0.0001
Fertilization	1	1.6536	1.6536	16.4	0.0001
T x F	1	0.8706	0.8706	8.65	0.0037
T x M	53	4.9764	0.0939	0.93	0.6061
F x M	53	5.0442	0.0952	0.95	0.5830
T x F x M	53	5.0378	0.0951	0.94	0.5852
Error b	162		0.1006		

df = degrees of freedom; SS = sum of squares; MS = mean square; Pr > F = probability of a greater F-value; M = month of year; T = thinning; F = fertilization.

Table 2—Analyses of variance of mean monthly loblolly pine root initiation rate (number per dm² per day) at the 0- to 5-, 5- to 15-, and 15- to 30-cm depths between 1993 and 1998 in response to thinning and fertilization

Source of variation	df	SS	MS	F-value	Pr > F
		0- to 5-cm depth			
Block	1	0.0424	0.0424	0.84	0.3634
Month of year	61	66.741	1.0941	21.6	0.0001
Error a	61		0.0506		
Thinning	1	0.2379	0.2379	5.47	0.0205
Fertilization	1	0.0044	0.0044	0.10	0.7520
T x F	1	0.0086	0.0086	0.20	0.6463
T x M	61	4.7404	0.0777	1.79	0.0017
F x M	61	3.2340	0.0531	1.22	0.1580
T x F x M	61	2.3240	0.0381	0.88	0.7239
Error b	186		0.0435		
		5- to 15-cm depth			
Block	1	0.0027	0.0027	0.09	0.7599
Month of year	61	27.990	0.4588	15.7	0.0001
Error a	61		0.0292		
Thinning	1	0.0491	0.0491	2.18	0.1416
Fertilization	1	0.0205	0.0205	0.91	0.3411
T x F	1	0.0286	0.0286	1.27	0.2614
T x M	61	1.3965	0.0229	1.02	0.4565
F x M	61	2.1569	0.0354	1.57	0.0118
T x F x M	61	1.1686	0.0192	0.85	0.7678
Error b	186		0.0225		
		15- to 30-cm depth			
Block	1	0.0636	0.0636	2.84	0.0973
Month of year	61	17.035	0.2793	12.5	0.0001
Error a			0.2243		
Thinning	1	0.1766	0.1766	9.58	0.0023
Fertilization	1	0.0847	0.0847	4.60	0.0334
T x F	1	0.0815	0.0815	4.43	0.0368
T x M	61	0.9873	0.0162	0.88	0.7181
F x M	61	1.5989	0.0262	1.42	0.0384
T x F x M	61	1.0672	0.0175	0.95	0.5836
Error b	61		0.0184		

df = degrees of freedom; SS = sum of squares; MS = mean square; Pr > F = probability of a greater F-value; M = month of year; T = thinning; F = fertilization.

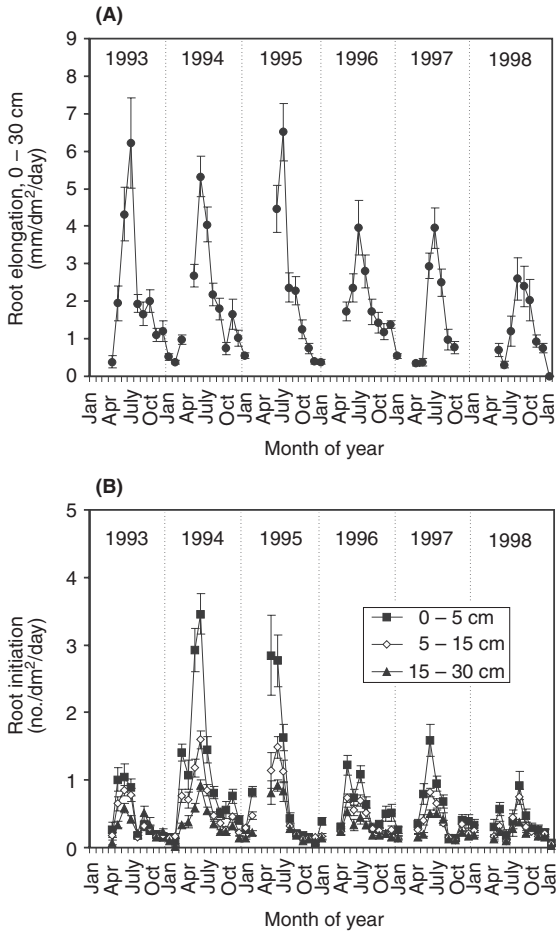

Figure 1—Mean monthly loblolly pine root elongation (A) and initiation (B) rates of loblolly pine in a loblolly pine plantation in central Louisiana, 1993–98.

and thinning was due to higher monthly root initiation rates in response to thinning in 1993, 1994, 1995, and 1997, but not in 1996 and 1998.

Root elongation rate at the 0- to 30-cm depth and root initiation rate at the 15- to 30-cm depth were significantly affected by an interaction between thinning and fertilization (tables 1 and 2). On the unthinned plots, lower rates of root growth were observed in response to fertilization, whereas on the thinned plots, root growth rates were not significantly affected by fertilization. A significant interaction between month of year and fertilization was observed for root initiation rates at the 5- to 15-cm and 15- to 30-cm depths. Root initiation in response to fertilization at the 5- to 15-cm and 15- to 30-cm depths in June and July of 1995 was greater than in all other months during the 6-year period.

Peak root elongation rate during May through October was significantly affected by year ($P = 0.0586$) (table 3), with higher rates of root elongation in 1993 through 1995 than in 1996 through 1998 (fig. 2). Similarly, the peak rate of root initiation was significantly affected by year, with the greatest root initiation rate in 1994 and 1995 and the lowest root initiation rate in 1998. We found that the peak root elongation rate at the 0- to 30-cm depth and root initiation rates at the 0- to 5-cm and 15- to 30-cm depths were significantly affected by thinning, with 45-percent and 22-percent greater root elongation and initiation rates, respectively, on the thinned plots than on the unthinned plots. We also found that a significant interaction between year and fertilization for peak root initiation rate at the 5- to 15-cm depth was due to a 38-percent higher rate of root initiation in response to fertilization in 1995.

Table 3—Probabilities of a greater F-value in the analyses of variance of peak loblolly pine root elongation rate (mm/dm²/day) at the 0- to 30-cm depth, root initiation rate (number/dm²/day) at the 0- to 5-, 5- to 15-, and 15- to 30-cm depths, and current annual stemwood biomass increment (Mg/ha/year) in response to thinning and fertilization in a loblolly pine plantation in central Louisiana, 1993 to 1998

		Elongation rate	Initiation rate			
		0–30 cm	0–5 cm	5–15 cm	15–30 cm	CAI
Source of variation	df	Pr > F				
Block	1	0.7962	0.2948	0.3047	0.8384	0.0752
Year	5	0.0586	0.0007	0.0025	0.0334	0.0214
Thinning	1	0.0005	0.0100	0.2054	0.0069	0.0001
Fertilization	1	0.0793	0.7112	0.9574	0.1074	0.0001
T x F	1	0.3247	0.9986	0.6801	0.9875	0.9880
T x Y	5	0.2906	0.1294	0.3196	0.7882	0.0920
F x Y	5	0.4049	0.0805	0.0376	0.0702	0.4656
T x F x Y	5	0.5374	0.8071	0.2128	0.7983	0.9414

CAI = current annual stemwood biomass increment; df = degrees of freedom; Pr > F = probability of a greater F-value; Y = year; T = thinning; F = fertilization.

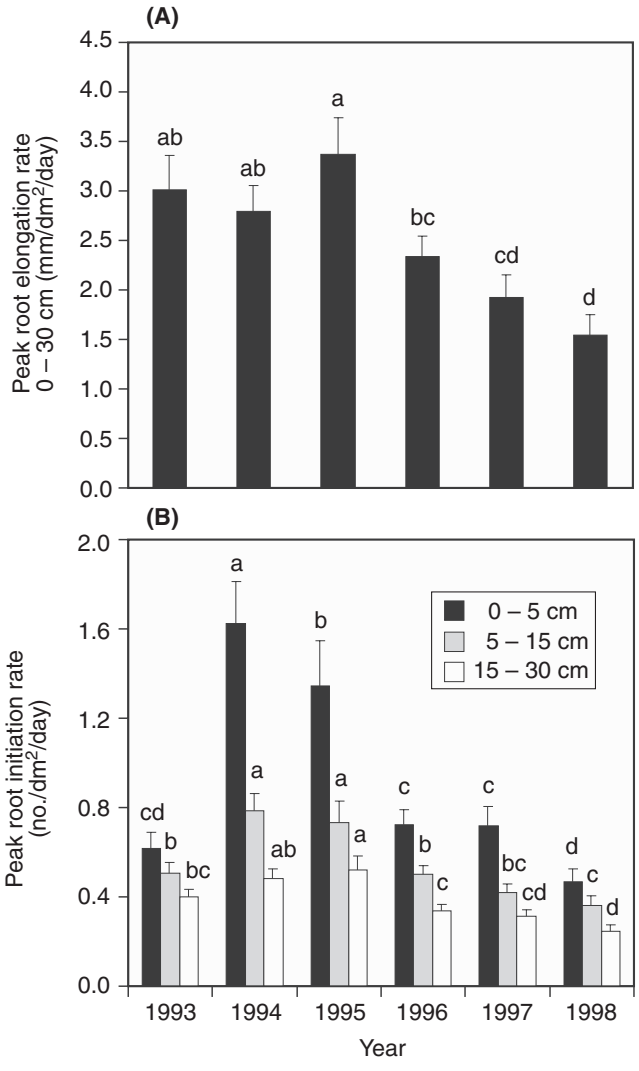

Figure 2—Peak loblolly pine root elongation rate at 0- to 30-cm (A) and initiation (B) rates in a loblolly pine plantation in central Louisiana, 1993–98. Means within a depth interval followed by a different letter are not significantly different at $P \leq 0.05$ by the least significant difference test.

Values of CAI differed significantly by year (table 3). The highest values of CAI were in 1994 (10.2 Mg/ha/year) and 1998 (9.9 Mg/ha/year), and the lowest values of CAI were in 1996 (5.7 Mg/ha/year) and 1997 (6.6 Mg/ha/year). Values of CAI in 1993 (7.5 Mg/ha/year) and 1995 (8.0 Mg/ha/year) were intermediate among the 6 years. Thinning and fertilization significantly affected CAI, with a 34-percent reduction in CAI in response to thinning and a 51-percent increase in CAI in response to fertilization.

We found significant linear relationships between peak root elongation rate and annual water deficit, and between peak root initiation rates at 5- to 15-cm and 15- to 30-cm and annual water deficit (fig. 3). These relationships suggest that root growth was directly and inversely related to annual water deficit.

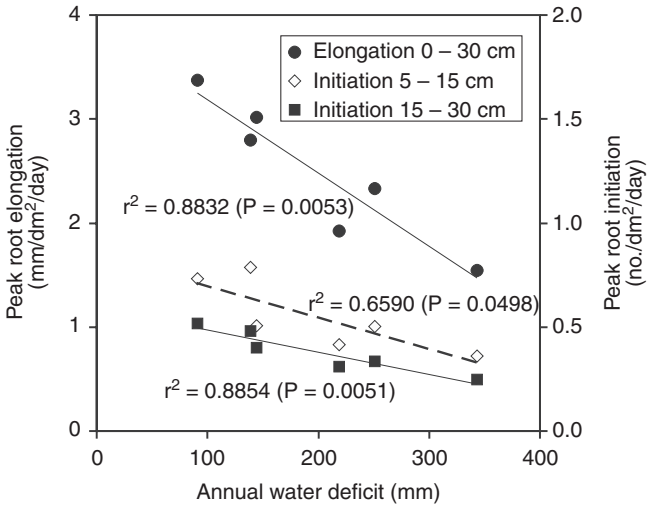

Figure 3—Relationships between peak loblolly pine root elongation and annual water deficit, and peak loblolly pine root initiation and annual water deficit in a loblolly pine plantation in central Louisiana, 1993–98. Values of r^2 are coefficients of determination.

When plot-level data for all years between 1993 and 1998 were combined, the relationship between CAI and cumulative root elongation between June and October was significant but was associated with a low coefficient of determination (table 4). When the relationships between CAI and cumulative root growth between June and October were evaluated for the 3 years of low water deficit (1993–95), significant relationships between CAI and both root elongation and root initiation at the 15- to 30-cm depth were found. The coefficient of determination and slope associated with this relationship indicates that these variables were directly and inversely related (fig. 4).

Relationships between plot-level CAI and cumulative root growth for the 3 years of high water deficit (1996–98) were not significant (table 4). For the 3-year period between 1996 and 1998, however, the chronological relationship between CAI and both cumulative root elongation and cumulative root initiation at the 15- to 30-cm depth between June and October were consistent among the four treatment combinations. Specifically, values of CAI increased and cumulative root growth between June and October decreased over time (fig. 5).

Table 4—Linear relationships between current annual stemwood biomass increment and cumulative root elongation (mm/dm²/day) and initiation[a] (number per dm² per day) during June through October in a loblolly pine plantation in central Louisiana, 1993 to 1998

Time	n	b_1[b]	b_2	Pr > F	r^2
Root elongation, 0 to 30 cm					
1993–1998	48	10.8	-0.0071	0.0108	0.1331
1993–1995	24	14.58	-0.0126	0.0010	0.3974
1996–1998	24	10.24	-0.0088	0.0688	0.1427
Root initiation, 0 to 5 cm					
1993–1998	48	7.08	0.0074	0.3878	0.0163
1993–1995	24	7.14	0.0095	0.3871	0.0342
1996–1998	24	9.33	-0.022	0.3321	0.0428
Root initiation, 5 to 15 cm					
1993–1998	48	7.02	0.012	0.5267	0.0088
1993–1995	24	8.28	0.003	0.9152	0.0005
1996–1998	24	7.94	-0.0087	0.8223	0.0023
Root initiation, 15 to 30 cm					
1993–1998	48	10.05	-0.037	0.1150	0.0531
1993–1995	24	13.70	-0.076	0.0399	0.1782
1996–1998	24	10.74	-0.075	0.0701	0.1414

CAI = current annual stemwood biomass increment; Pr > F = probability of a greater F-value; r^2 = coefficient of determination.
[a] Cumulative root elongation and initiation were measured in rhizotrons as the sum of root elongation and initiation since June for the months between June and October.
[b] Model: $Y = b_1 + b_2 (X)$ where Y = CAI, X = root elongation at 0 to 30 cm or root initiation at 0 to 5 cm, 5 to 15 cm or 15 to 30 cm, and b_1, and b_2 are coefficients estimated from the data.

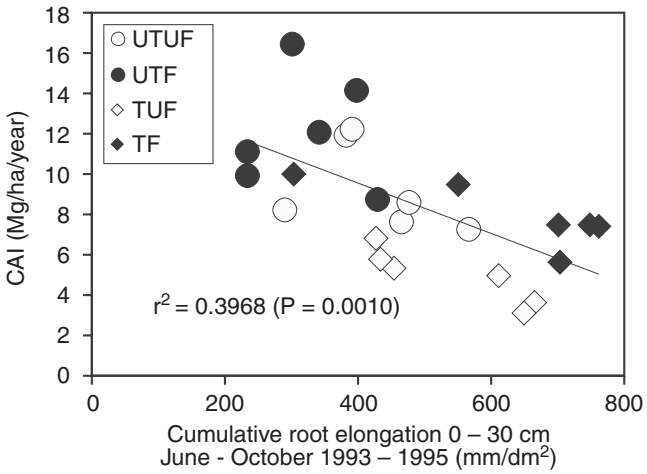

Figure 4—Relationship between current annual stemwood biomass increment (CAI) and cumulative root elongation between June and October 1993–95 in a loblolly pine plantation in central Louisiana. Treatment combinations are unthinned and unfertilized (UTUF), unthinned and fertilized (UTF), thinned and unfertilized (TUF), and thinned and fertilized (TF), and r^2 is the coefficient of determination.

DISCUSSION

The seasonal pattern of loblolly pine root elongation and initiation was multimodal, with a large peak in May through October and smaller intermittent peaks in September through December. This distinct seasonal pattern suggests that annual expansion of the loblolly pine absorbing root network is dependent on new root growth within a relatively narrow window of the growing season.

During this window of root growth, the soil conditions next to the growing roots may influence the magnitude of annual root system expansion. For example, Gulf Coastal Plain soils are commonly characterized by the formation of a winter water table within 200 cm of the soil surface (Soil Survey Staff 1998). An extended period of soil saturation in spring could limit the availability of oxygen for root metabolism early in the period of peak new root growth (Sword and Tiarks 2002). On the other hand, because summer droughts are common on the Gulf Coastal Plain (Allen and others 1990, Dougherty 1996), reductions in soil water content that result in high soil strength may inhibit root elongation later during peak new root growth (Sword and Tiarks 2002).

The relationships we found between annual water deficit and root growth during our 6-year study suggest that water availability greatly influenced root system expansion. For example, we found that new root growth decreased as annual water deficit increased. Since soil water potential and soil strength become more root-growth-limiting as the soil dries (Bennie 1996, Kaufmann 1968, Torreano and Morris 1998), the depletion of soil water associated with high annual water deficit may have created soil environmental conditions that limited new root growth. Also, although maximum root growth occurred in May through July, in years of high water deficit this peak was delayed until precipitation occurred. This response suggests that a surge of new root growth occurs when the conditions that limit new loblolly pine root growth are alleviated.

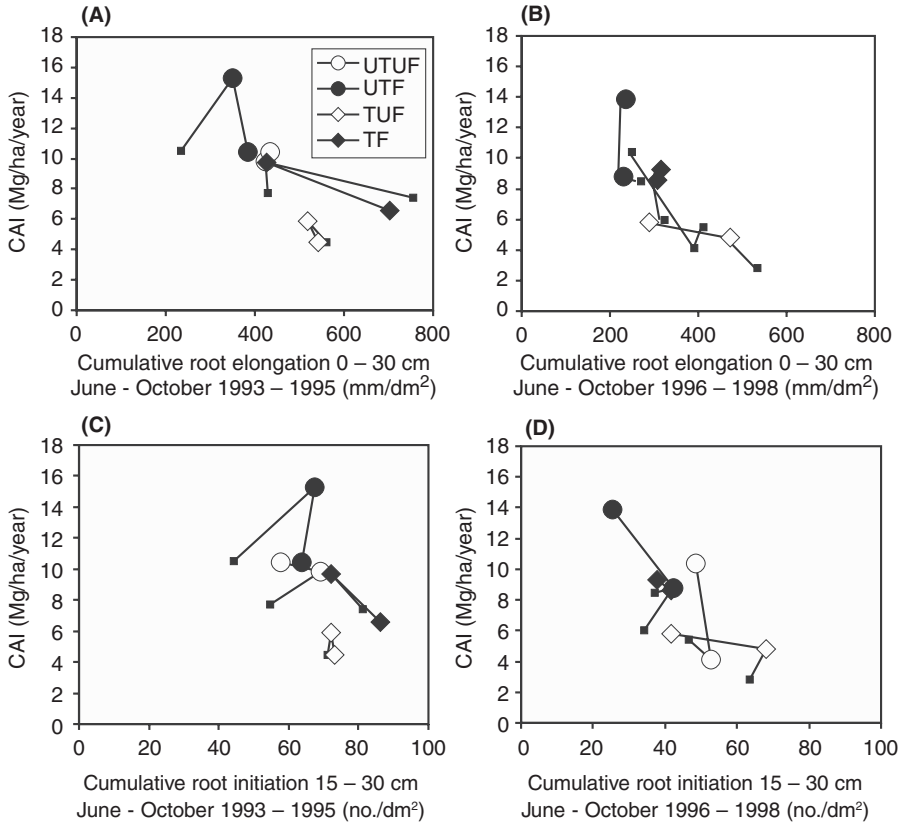

Figure 5—Relationships between current annual stemwood biomass increment (CAI) and cumulative loblolly pine root growth for the 3 years of low water deficit (A and C) and the 3 years of high water deficit (B and D) in a loblolly pine plantation in central Louisiana, 1993–98. Treatment combinations are unthinned and unfertilized (UTUF), unthinned and fertilized (UTF), thinned and unfertilized (TUF), and thinned and fertilized (TF). The beginning of the age sequence for each treatment combination is noted with the small square symbol.

Over the 3-year period of high water deficit, declines in new root growth became more severe. At the same time, progressive decreases in predawn needle water potential and net photosynthesis occurred.[2] In addition to root-growth-limiting soil properties, therefore, negative effects of high water deficit on crown physiology and the availability of carbohydrates for root metabolism may have inhibited new root growth as the 3-year period of high water deficit progressed.

Throughout the 6-year study period, we observed consistently higher rates of root growth in response to thinning. Regardless of water deficit, therefore, light availability in the crown appeared to consistently influence new root growth. In contrast, root growth responses to fertilization were limited to 1995. In early 1995, foliar P concentrations reached deficient values for loblolly pine (1.0 mg/g) (Allen 1987), on both the unfertilized (0.67 mg/g) and fertilized (0.96 mg/g) plots.[3] Since P nutrition strongly affects root growth (Marschner 1986), greater root growth rates immediately after refertilization may have been caused by the alleviation of P limitations to root growth.

During the 3-year period of low annual water deficit between 1993 and 1995, we observed a negative relationship between plot-level CAI and cumulative root growth. Past research has shown that as the availability of essential resources decreases, carbon (C) is preferentially allocated to belowground rather than aboveground growth (Haynes and Gower 1995; Keyes and Grier 1981; Santantonio and Santantonio 1987; Vogt and others 1983, 1987). The CAI and cumulative root growth data from 1993-95 reflect this relationship. On the unthinned plots, however, low rates of net photosynthesis in the lower crown due to light limitations (Gravatt and others 1997, Tang and others 1999) and subsequent reductions in the amount of C allocated for root metabolism may have interfered with the fundamental relationship between resource availability, CAI, and cumulative root growth.

We did not find any consistent relationships between CAI and cumulative root growth among the treatment combinations during the 3-year period of high annual water deficit. As the 3 years of high water deficit progressed, however, a consistent relationship between CAI and cumulative root growth was observed among the treatment combinations. Specifically, cumulative root growth decreased or was unchanged, while CAI increased. We hypothesize that water deficit limited root growth in the 0- to 30-cm depth but

[2] Tang, Z. Unpublished data.
[3] Sword-Sayer, M.A. Unpublished data.

stimulated root growth below 30 cm. As C was allocated for the metabolism and growth of deep roots, water became less limiting to CAI. Absorbing roots may have migrated deeper in the soil profile so that by the third year of high water deficit, adequate water was supplied for high rates of stemwood production.

In summary, the new root growth of loblolly pine at our study site was characterized by a distinct maximum that occurred over a 3-month period between May and October. Water deficit altered both the magnitude of new root growth and the timing of the peak period of root growth. Furthermore, regardless of water deficit, root growth was closely associated with light availability in the canopy. As we learn more about how soil conditions and carbohydrate availability affect new root growth, this information will improve our ability to manage root system growth and predict the supply of soil resources for stand production. We also found an inverse relationship between CAI and cumulative root growth during the 3-year period of low water deficit, which suggests that C was preferentially allocated to aboveground growth rather than belowground growth along a gradient of stand conditions. This relationship was absent during the 3-year period of high annual water deficit. At this time, however, a consistent inverse relationship between CAI and cumulative root growth was observed among the treatment combinations, which may indicate that by the third year of high annual water deficit, the growth of absorbing roots had adapted so that adequate water was available for high rates of stemwood growth.

ACKNOWLEDGMENTS

The authors gratefully acknowledge Dan Andries for his dedicated, long-term maintenance of the rhizotrons, and Jim Barnett and Jim Chambers for their continued support of root research at the study site.

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STEM SINUOSITY OF LOBLOLLY PINE SEEDLINGS AS INFLUENCED BY TAPROOT SHAPE

Michael S. Murphy and Timothy B. Harrington[1]

Abstract—Sinuous stem growth in loblolly pine (*Pinus taeda* L.) results in diminished potential for the utilization of wood products since these stems are difficult to mill and contain a higher percentage of compression wood. In this study, 90 full-sibling loblolly pine seedlings (30 seedlings from each of 3 families) were planted with 5 taproot configurations: straight taproot (check treatment), straight taproot with underground obstruction, taproot planted with "J" shape, straight taproot planted at a 45 degree angle, and a straight taproot with the stem guy-wired to a 45 degree angle. Seedlings were irrigated and fertilized to maintain high growth rates, and insect control treatments were applied to minimize injury from the Nantucket pine shoot tip moth (*Rhyacionia frustrana* Comstock). Growth and form data were collected after the first growing season. Statistical analyses were conducted to determine if seedling growth rate and stem eccentricity varied significantly according to family, taproot treatment, or their interaction.

INTRODUCTION

Sinuous stem growth, an oscillating curvature of the stem, may be caused by taproot deformity. Sinuous trees contain more compression wood, which is one of the mechanisms in gymnosperms responsible for stem curvature. However, compression wood is undesirable for wood utilization purposes. It comprises 10–15 percent of wood volume in southern pines (Timell 1986) and results in warping of lumber, which has less strength under tension, creating a product that may endanger life and property (Koch and others 1990). It is also undesirable for pulpwood utilization because of its high lignin and low cellulose contents, leading to reduced pulp yield and quality (Low 1964). If it can be determined that taproot deformity is a cause of stem sinuosity, alternative planting procedures could be developed to reduce compression wood formation.

Compression wood corrects a bent stem to its normal position by longitudinal expansion on the concave side of the stem. Sinuosity is a result of an overcorrection, when the stem is bent back into a bend in the opposite direction (Timell 1986). This series of oscillating curves continues up the stem until equilibrium is reached and normal growth resumes. Sinuous condition usually remains for the life of the tree. Although the exact mechanism is unknown, gravitational stimulus is commonly accepted as a cause of compression wood formation (Koch and others 1990, Sinnott 1952). However, recent research has shown that compression wood can form in the microgravity environment of the NASA space shuttle (Kwon and others 2001).

Planting methods that result in compressed and/or bent lateral roots and taproots are a suspected cause of stem sinuosity (Harrington and others 1999). The presence of a soil hardpan can mimic these conditions by providing an impenetrable obstruction resulting in taproot bending. Balneaves and De La Mare (1989) compared tree growth and root development in soils with a known mineral hardpan. Treatments consisted of ripping the soils to varying depths and no ripping. Greater taproot penetration was found on the ripped sites when compared to unripped sites. The least amount of stem deviation was found on those sites with the straightest and deepest penetration of taproots.

Conversely, other studies indicate root deformation has no negative effects on survival and growth. Although the problems of compression wood and stem sinuosity were not addressed directly in these cases, these studies show that early growth is greater for trees with deformed root systems (Hay and Woods 1974a, 1974b, Seiler and others 1990, Woods 1980). This may occur because deformed roots develop more lateral roots near the soil surface, and these laterals are more important than deep taproots for absorbing limited soil moisture during dry periods (Hay and Woods 1974b). Deformed roots also may improve wind resistance due to their increased upper lateral root growth (Hunter and Maki 1980, Seiler and others 1990). They could, however, hinder later growth because as deformed roots grow in their twisted condition some break and die, making the tree more susceptible to windfall, insects, and disease (Hay and Woods 1974a).

Although the majority of the literature assumes that root deformity has no negative effect on growth and survival, few researchers have addressed the problem of stem form in association with root deformity. Harrington and others (1999) performed a retrospective study on machine planted loblolly pine to assess the relationship between stem sinuosity and root deformation. Trees identified as having sinuous characteristics were assigned to an index that correlated with their degree of sinuosity. These trees were then excavated and their root systems examined. The results indicated a potential correlation between bent taproots and reduced stem quality. This study's objective is to show a relationship between sinuous stem growth and taproot deformation in newly planted seedlings.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

MATERIALS AND METHODS

Study Site Description

This study was located at Whitehall forest in Athens, GA. Development of planted pine seedlings was studied both in raised beds and in an open field. Both the beds and the field were tilled to a 30-cm depth prior to planting. Competing vegetation was controlled using glyphosate herbicide. The bare mineral soil was mulched with pine straw to maintain soil tilth and suppress development of competing vegetation. Seedlings were irrigated throughout the growing season with soaker hoses and fertilized with macro- and micro-nutrients.

Study Design

The experimental design of the study is a randomized complete block with a factorial arrangement of treatments. Five taproot treatments were applied to three full-sibling families. The taproot treatments included a straight taproot/straight stem planting (check treatment), a straight taproot with obstruction planting, a j-root planting, an angled taproot/stem planting, and a straight taproot/angled stem planting. The three full-sibling families were selected for their stem straightness characteristics. Each combination of the 5 taproot treatments and 3 families was replicated 6 times, resulting in a total of 90 seedlings. Treatment replications were grouped in blocks, and three blocks each occurred in the raised beds and in the field.

An effort was made to create identical soil disturbance conditions for each taproot treatment. The taproot obstruction required the use of a 45-cm x 45-cm plexiglass sheet. A square area was excavated and the plexiglass was placed at a depth of 20 cm. This same large excavation was done for each planting. The angled planting was done by holding the entire tree at a 45 degree angle as soil was filled around it. The straight taproot/angled planting was done by planting the tree with a straight taproot. The tree stem was then pulled over to a 45 degree angle with a wire and maintained in that position by securing the wire to a stake.

Measurements

Measurements of stem diameter (at 1 cm above ground), height, and frequency and amplitude of stem curvature were collected on October 8, 2002, one growing season after planting. Frequency of stem curvature was determined as the number of interwhorl curves that occurred in the main stem. Amplitude of stem curvature was measured as the distance from the peak of each stem curve and a vertically held straight edge. These values were averaged for the entire stem of each tree.

Statistical Analysis

The variables of stem diameter, height, frequency, and amplitude were subjected to analysis of variance to determine if tree size and stem curvature varied significantly ($\alpha = 0.05$) among taproot treatments, families, or their interactions. Multiple comparisons of treatment means were conducted with Tukey's test. All analyses were performed with SAS (SAS Institute 1989).

RESULTS AND DISCUSSION

Taproot Treatment

Stem diameter and frequency of stem curvature varied significantly among taproot treatments while height and amplitude did not (table 1). Seedlings planted with a "J" shaped root had the smallest values for stem diameter. Frequency was greater for the treatments which had a higher diameter (fig. 1). In general, the largest seedlings had the greatest frequency of stem curvature.

Family

Stem diameter, height, frequency, and amplitude of stem curvature each varied significantly among families. Family (A) significantly outgrew the other families in height. This growth likely affected frequency, resulting in a significant difference in family (A) from the other families (fig. 2). It is difficult to say if the expression of sinuous characteristics is a result of the increased growth of family (A) or a symptom of the genetic characteristics of this family. As with treatment, measurements collected during the second growing season may provide clarification.

Interaction Effects

While significant differences existed among taproot treatments and families, there were no significant treatment interactions.

CONCLUSIONS

The preliminary data collected during the first growing season indicate some differential growth responses to taproot treatment and family. In general, seedlings with greater growth had more pronounced levels of stem sinuosity. By comparing tree responses among the taproot treatments we hope to identify planting or planting spot characteristics that are associated with increased levels of stem sinuosity. Seedling growth and sinuosity responses will be monitored for a second growing season. In addition,

Table 1—Significance levels for the effects of taproot treatment, family, block, and their interaction. Factors are considered significant if $P \leq 0.05$

Variable	Treatment	Family	Interaction	Block
Diameter	0.0382	0.0081	0.8548	0.8682
Height	0.5778	0.0003	0.9863	0.9608
Frequency	0.0122	< 0.0001	0.0977	0.1986
Amplitude	0.1121	0.0035	0.2352	0.0447

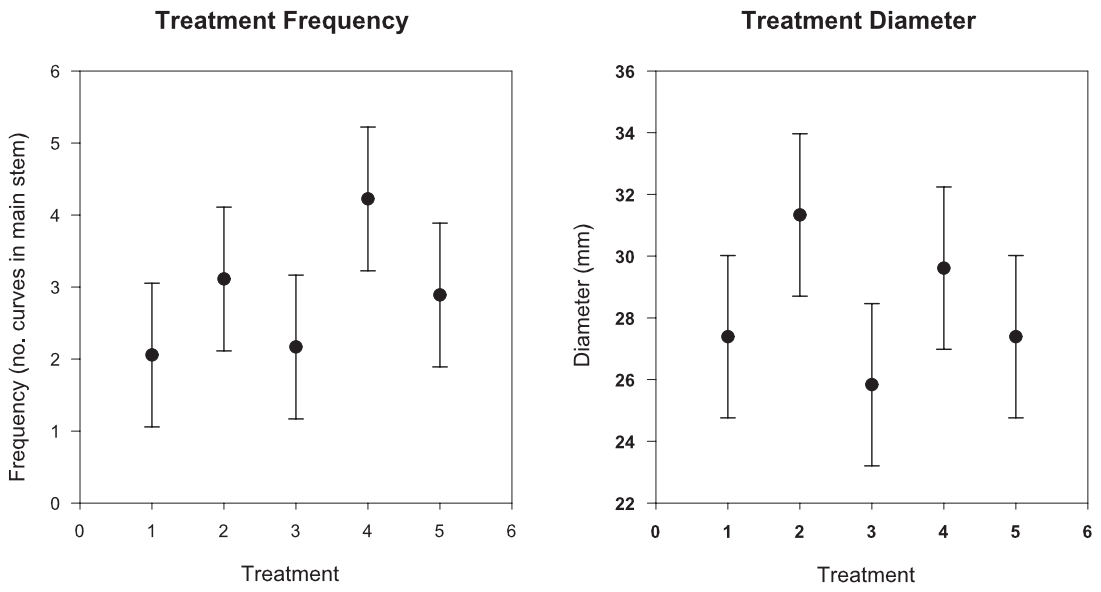

Figure 1—Comparisons of taproot treatment means, with 95 percent confidence intervals for frequency and diameter. Taproot treatments are 1-check (straight taproot, straight stem), 2-taproot obstruction, 3-J-root treatment, 4-angled planting, 5-straight taproot, stem angled.

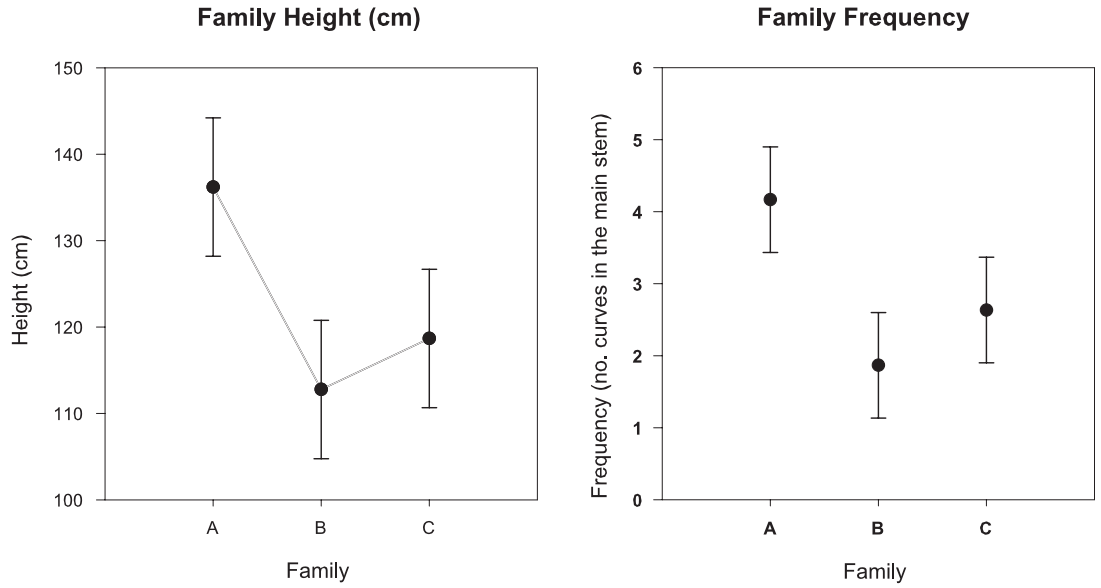

Figure 2—Comparisons of family means, with 95 percent confidence intervals for frequency, and height.

trees will be harvested and evaluated for different wood properties among the treatments.

Ongoing measurements in existing field studies also are underway. Specifically, data are being collected in 6-year old plantations that have straight, "J", and "L" shaped taproot plantings. Three of these plantations are comprised of loblolly pine and three are slash pine (*Pinus elliotti*). To determine if tree responses are influenced by availability of belowground resources, plots for each planting treatment are split with half receiving N+P fertilization and herbaceous weed control and half receiving neither of these treatments. As in the seedling study, stem diameter, height and the frequency and amplitude of stem curvature are being collected on these trees.

ACKNOWLEDGMENTS

We would like to thank Mike Hunter and Dale Porterfield of Whitehall Forest for providing the facilities and assistance. We would also like to thank Terry Price of the Georgia Forestry Commission for initiating the idea behind this experiment. Thanks to Mike Cunningham of International Paper for providing the full-sibling seedlings. Finally, we would like to thank Richard Daniels, Laurie Schimleck,

Mike Huffman, Gopal Ahuja, and Doug Marshall for their assistance.

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SOIL CO_2 EFFLUX TRENDS FOLLOWING THE THINNING OF A 22-YEAR-OLD LOBLOLLY PINE PLANTATION ON THE PIEDMONT OF VIRGINIA

M.F. Selig and J.R. Seiler[1]

Abstract—Due to the growing concern over increasing atmospheric CO_2 concentrations, it has become increasingly important to understand the influence forest practices have on the global carbon cycle. The thinning of loblolly pine (*Pinus taeda*) plantations in the Southeastern United States is a common silvicultural practice and has great potential to influence carbon fluxes. In order to quantify the effects of thinning on CO_2 efflux (E_c), measurements were taken monthly for 1 year, following the thinning of a 22-year-old loblolly pine stand. Soil moisture and temperature were measured concurrently with respiration. E_c measurements were taken at positions adjacent to trees and new stumps, as well as 1.22 m away. E_c appeared to exhibit a slight increase in thinned stands; however, all significant differences were explained by the higher temperatures in thinned stands. This suggests that other than through increasing temperature, thinning does not significantly affect soil E_c, as gains and losses in respiration from many altered biological processes may cancel each other out.

INTRODUCTION

It is estimated that 40 percent of all belowground carbon is located in forest soils (Dixon and others 1994). Loblolly pine (*Pinus taeda*) plantations currently occupy over 13 million ha of forested soils in the Southeastern United States (Shultz 1997). Therefore, forest operations within these managed stands that impact the carbon cycle have the ability to greatly affect global carbon dynamics by altering growth and decomposition above and below ground.

The thinning of pine plantations is a commonly used silvicultural procedure. The process involves the systematic harvest of several trees from a young stand, with the intent of re-allocating growth from many small trees to fewer large trees. This practice will invoke both physiological and growth responses for the remaining trees and microclimatic changes within the modified stand (Smith and others 1997). Remaining trees will have increased growth rates (Ginn and others 1991, Peterson and others 1997) and eventually basal area and volume of thinned stands will converge on levels equal to unthinned stands (Della-Bianca and Dils 1960, Hasenauer and others 1997, Pienaar and others 1985) resulting in equal aboveground carbon sequestration and inputs into the system.

As stumps and root systems from harvested trees sit in the newly modified stand, increased forest floor temperatures and soil moisture will begin to decompose the belowground biomass (Della-Bianca and Dils, 1960, Nowak and others 1990). Thinning will affect root activity of remaining trees through its influence on environmental and physiological variables such as light, mineral nutrient and water availability, and photosynthate production and partioning (Santantonio and Santantonio 1987). Thinning may also help promote root growth by providing root channels from decomposing roots of harvested stumps. Van Lear and others (2000) showed that the concentration of resources and low soil strength in root channels from trees harvested 10 years prior provided a favorable rooting environment for remaining trees.

The effects of thinning will likely alter E_c within the modified stand. E_c is the combination of heterotrophic and autotrophic respiration. Heterotrophic respiration refers to the CO_2 emitted from microbial activity (decomposition of organic matter) within the soil. Autotrophic respiration is considered to be the sum of direct root and associated microbial rhizosphere respiration (Hanson and others 2000). Global E_c rates have been estimated to be between 60-80 Pg (1×10^{15} g) of carbon per year (Raich and Potter 1995, Raich and Schlesinger 1992, Schlesinger 1977) with an estimated 598 gC per m^2 per year coming from temperate pine forests (Schlesinger 1977). These carbon dioxide emissions from soils exceed all other terrestrial atmospheric carbon exchanges with the exception of gross photosynthesis (Raich and Schlesinger 1992).

The thinning of a loblolly pine stand will lead to a complex mix of CO_2 fluxes from the soil. Root systems of harvested trees will likely die, unless grafting occurs, reducing autotrophic respiration. Remaining trees will likely increase root growth and respiration, reoccupying the site. Temporary autotrophic respiration additions may also be seen from advantageous understory growth. Decomposition of old roots will also increase heterotrophic respiration rates. The objective of this study was to determine how all of these individual processes caused by the thinning of a 22-year-old plantation would affect soil CO_2 E_c trends over the course of one year following harvest.

METHODS AND MATERIAL

Study Site

The study site is located on the upper Piedmont at the Reynolds Homestead Forest Resources Research Center in Critz, VA. The area receives an average of 1,150 mm of precipitation, maintains an average annual temperature of 14.3 °C, a maximum mean temperature of 21.3 °C, a minimum annual average of 7.3 °C and 193 frosted days extending from mid-March through mid-October (NOAA 2001).

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Historically, this land was in agricultural fields until 1980 when three replicate 0.222-ha sites were planted with loblolly pine seedlings, using 3.05-m by 3.05-m spacing. Stand one is located on a Lloyd clay loam, and stands two and three are located on a Wickham loam. In March of 1988, half of each stand was thinned diagonally, leaving square spacing of 4.31 m by 4.31 m. Crown closure was reached again approximately 6 years after the thinning.

The thinned section of the stand was thinned again in April 2002 by the removal of every other row of trees. A majority of the slash was removed from the site. The resultant treatment then contained 22-year-old loblolly pines at 6.1-by 6.1-m spacing and a mix of new and old stumps. Following the second thinning, thinned stands had a basal area of 23.0, 20.8, and 18.9 m^2 per ha while unthinned stands maintained 55.1, 59.0, and 49.7 m^2 per ha in blocks one, two, and three respectively.

Experimental Layout

Past studies (Pangle and Seiler 2002, Wiseman 2001) have revealed a strong measurement position effect on E_c. Measurements taken near trees have significantly higher E_c rates. Therefore, measurements were taken both near and away (approximately 1.22 m away) from trees and stumps. To adequately characterize the effect of thinning on E_c, measurements were taken both near and away from thinned trees, new stumps, and old (1988 thinning) stumps. In the unthinned treatment, measurements were taken near and away from trees. Four locations in each treatment were identified and measured and used as subsamples. Near and away positions were analyzed in the analysis as a split.

Soil Respiration Measurements

E_c measurements were taken monthly beginning in February 2002, 2 months prior to thinning and continued for 1 year following thinning. E_c was measured using the LiCor 6200 infrared gas analyzer (LiCor Inc., Lincoln, NE). A dynamic closed cuvette chamber system was used in conjunction with the LiCor 6200. The cuvette chamber was constructed using PVC piping for walls, a plexi-glass top, and an aluminum edge on the bottom. The chamber has an internal diameter of 25.5 cm, stands 13.5 cm tall, and has an entire system volume of 6,744 cubic cm. The aluminum edge on the bottom of the chamber allowed it to cut through needles on the forest floor, reducing error imposed by sub-litter airflow caused by windy conditions.

The LiCor 6200 was recalibrated before every day of data collection. The system was zeroed before data collection at every block. Measurements were taken at the base of the tree, new stump, or old stump, and approximately 1.5 m away from the object. Effort was taken to place the chamber on bare forest floor, as photosynthesizing or respiring vegetation will alter E_c measurements.

Respiration rates were determined by measuring E_c for a continuous 30-second period. The LiCor 6200 then calculated the E_c rate using equation (1):

$$\text{Soil } E_c = [(\Delta C/\Delta t)(PVt/RT)] / \text{Area} \quad (1)$$

where $C = [CO_2]$, t = time (30 seconds), P = atmospheric pressure, Vt= system volume, R = universal gas constant, and T = temperature.

Soil Moisture and Temperature

Soil moisture and temperature were measured concurrently with E_c. Soil moisture was measured to a depth of 12 cm using a HydroSense moisture meter (Campbell Scientific, Australia). Measurements are expressed as a volume percent. Temperature was measured to a depth of approximately 7 cm using a Digi-sense temperature gauge (Cole-Parmer Instrument Co., Niles, IL), and expressed to the nearest 0.1 °C.

Statistical Analysis

Analysis of variance was performed using a split-block design using JMP IN® statistical discovery software Version 4 (SAS Institute, Cary, NC). Two analyses were performed. In one analysis, E_c of thinned trees, unthinned trees, new stumps, and old (1988 thinning) stumps were compared separately for each sampling date. In a second analysis, thinned and unthinned average E_c was compared. Soil temperature was later added to each model as a covariate to determine if differences found were due primarily to changes in soil temperature.

A time series analysis was also performed to detect differences between treatment types and location of treatment types over the 1 year sampling regime, by using sampling date as a split in the ANOVA.

RESULTS

E_c ranged from 0.0934 to 17.98 μmolCO_2 per m^2 per second in thinned stands and 0.1032 to 14.400 μmolCO_2 per m^2 per second in unthinned stands. E_c was higher in thinned stands on 8 out of 12 sampling dates (fig. 1). The difference in E_c between thinned and unthinned stands was only statistically significant on 3 of the 12 sampling dates ($p < 0.10$) (fig. 1). E_c was higher in the thinned stands on

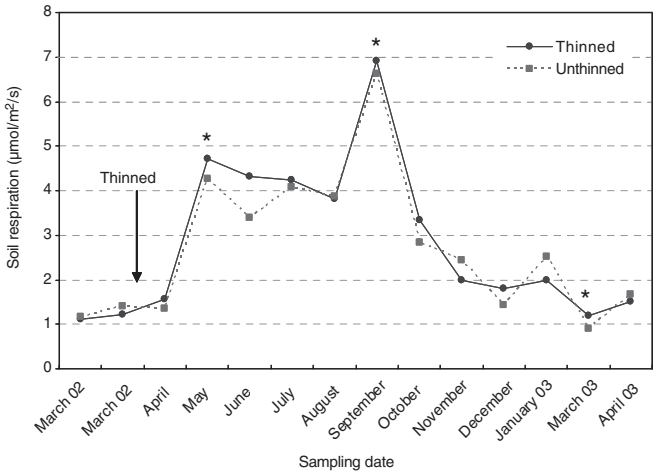

Figure 1—Soil respiration rates of thinned and unthinned 22-year-old loblolly pine plantations on the piedmont of Virginia, thinned April, 2002. An asterisk indicates a significant difference between thinned and unthinned stands ($p < .10$).

all three of the significant dates. However, when soil temperature was used as a covariate in the ANOVA for the May, December, and March dates, the difference between the thinned and unthinned stands became insignificant.

Soil temperature ranged from 3.1 to 25.8 °C in thinned stands and 3.8 to 22.5 °C in unthinned stands. Temperature was significantly different between the thinned and unthinned stands for 10 of the 12 sampling dates (fig. 2). Temperature was significantly higher in the thinned stands for the March and May sampling dates. On the December sampling date temperature was significantly lower in the thinned stands.

Figure 3 illustrates that there is no discernable pattern or significant difference in E_c between the new stumps, 14-year-old stumps, trees in the thinned stands, and trees in the unthinned stands on any date. This figure also illustrates the high variability between the different measurement plots within the thinned stands.

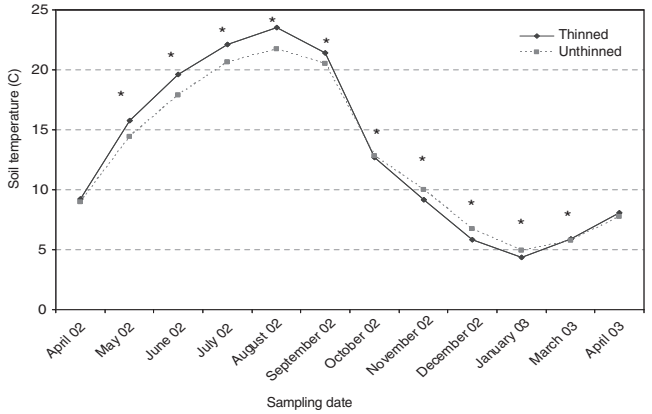

Figure 2—Soil temperature of thinned and unthinned stands of a 22-year-old loblolly pine plantation on the Piedmont of Virginia. An asterisk indicates a significant difference between thinned and unthinned stands ($p < .10$).

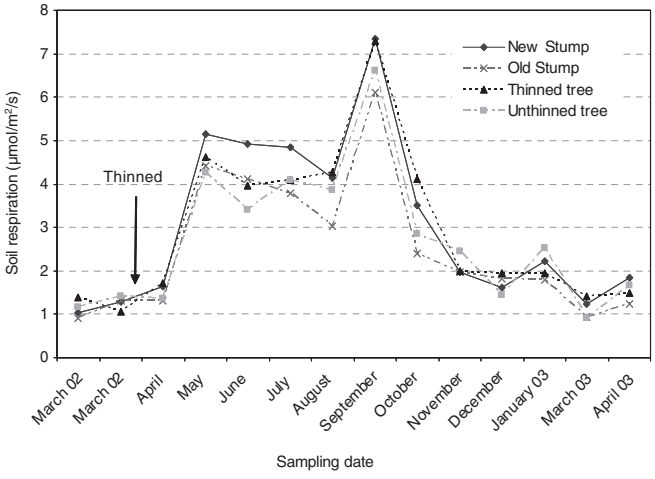

Figure 3—Soil respiration rates of new stumps, old stumps, trees located within a thinned stand and trees located within an unthinned 22-year-old loblolly pine plantation on the Piedmont of Virginia, thinned April, 2002.

DISCUSSION

While there does appear to be a slight increase in E_c following thinning, this is likely explained by altered soil temperatures. Thinning does have a significant effect on soil temperature on 10 of the 12 sampling dates, and any significant increase in E_c disappears once temperature is used as a covariate. Nowak and others (1990) and Della-Bianca and Dils (1960) also observed increases in soil temperature following thinning. Temperature is already known to be a significant driver of E_c (Trumbore and others 1996).

The lack of a strong difference between thinned and unthinned stands is also likely due to a variety of altered biological processes canceling each other out. Popescu (2001) observed a decrease in E_c following a clearcut of a loblolly pine stand on the Piedmont of Virginia. This was attributed to the loss of root respiration following the harvest of the trees. Therefore, the expected loss of root respiration caused by the harvesting of half of the trees in the thinned stand is likely being compensated for by the increased heterotrophic respiration supplied by the decomposition of dying roots. Van Lear (2000) and Santantonio and Santantonio (1987) both observed that thinning will likely increase growth of remaining trees. Increased growth rates of remaining roots are possibly increasing root respiration, again helping to buffer the loss in respiration suffered from the harvest of trees. The erratic patterns of E_c from the different types within the thinned stand may be a result of the variety of biological processes taking place after the disturbance.

Further work is needed to determine the individual underground processes that cause this phenomenon. The separation of autotrophic and heterotrophic respiration, as well as monitoring of root decomposition, would aid in explaining the true drivers.

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THE PHYSIOLOGY AND BIOCHEMISTRY OF DESICCATING WHITE OAK AND CHERRYBARK OAK ACORNS

Kristina F. Connor and Sharon Sowa[1]

Abstract—The recalcitrant behavior of white oak (*Quercus alba* L.) and cherrybark oak (*Q. pagoda* Raf.) acorns was examined in terms of effects of moisture content on seed longevity, viability, and biochemistry. Acorns of both species were fully hydrated and then subjected to drying under ambient conditions of temperature and relative humidity. Acorns were sampled regularly for moisture determination (gravimetric analysis), germination, and Fourier transform infrared spectroscopic analysis. Invertase activity was also determined in the desiccating white oak acorns. Transmission/reflectance spectra were collected on dry and rehydrated samples of cotyledon and embryonic axis tissue. Germination was highly dependent on initial acorn moisture content, and there were significant changes in lipid profiles of desiccating embryonic axis and cotyledon tissues during short-term drying. A strong absorbance near 1740/cm in cherrybark cotyledon tissue indicated a high concentration of ester carbonyl groups (storage lipids). Additionally, in acorns of both species, evidence of reversible shifts between gel and liquid crystalline phases were found in membranes of axes and cotyledons. Gas chromatographic analyses of desiccating white oak acorns revealed significantly greater sucrose concentrations in embryonic axes than in cotyledons; also, sucrose concentrations dropped dramatically with onset of root extension. It is possible that elevated sucrose concentrations afford protection against cell collapse and cell-wall membrane damage during moisture stress.

INTRODUCTION

Desiccation-resistant seeds can be dried without damage to moisture content (MC) of $\leq$ 12 percent and stored for long periods of time, while recalcitrant, or desiccation-sensitive, seeds cannot (Roberts 1973). This susceptibility makes any period of storage for some recalcitrant seeds very short, while others, such as water oak (*Quercus nigra* L.), can survive for 3 years under proper storage conditions (Connor and Bonner 1999, Connor and Sowa 2001). Hypotheses to explain the physiological basis of recalcitrance include (1) changes in membrane and storage lipids (Flood and Sinclair 1981, Pierce and Abdel Samad 1980); (2) physical disruption of seed membranes (Seewaldt and others 1981, Simon 1974); (3) changes in seed proteins and carbohydrates (Bochicchio and others 1997, Finch-Savage and others 1994, Greggains and others 2000); (4) changes in the water properties of desiccating seeds (Farrant and others 1985, 1988); and (5) aberrant metabolic processes during hydrated storage and as water is lost (Pammenter and others 1994). To date, the storage of some recalcitrant seeds is still an insurmountable problem.

MATERIALS AND METHODS

We collected white oak acorns (*Q. alba* L.) locally in Starkville, MS, within 2 days of shedding. Cherrybark oak (*Q. pagoda* Raf.) acorns were purchased from a commercial supplier. Acorns were soaked overnight in tap water prior to the experiments to insure full hydration. We conducted short-term desiccation experiments over 2 consecutive years. We spread acorns in a single layer on a lab bench to dry them and, at regular intervals, took subsamples and performed five analyses.

Germination Tests

We randomly selected and germinated 100 acorns as 2 replications of 50 seeds each. After imbibing in tap water overnight, acorns were cut in half. The half with the cup scar was discarded (Bonner and Vozzo 1987), and the pericarp was removed from the remaining half. Acorns were placed cut side down on moist Kimpak®. White oak acorns were germinated under a diurnal cycle of 20 °C for 16 hours in the dark and 30 °C for 8 hours with light, and cherrybark acorns were germinated under greenhouse conditions. Germination was tallied each week for up to 4 weeks. An acorn was scored as germinated if both the radicle and shoot had emerged and exhibited normal morphology and growth.

Moisture Content

We determined MCs of whole acorns using four to five replicates of three white oak acorns and four cherrybark oak acorns each. The randomly selected acorns were cut into quarters and dried in aluminum cans at 103$\pm$2 °C for 17$\pm$1 hours in a mechanical convection oven. We calculated seed MC on fresh-weight basis (Roberts 1973).

Carbohydrates

We dissected white oak embryonic axes with immediately adjacent cotyledon tissue from the acorns; tissues were frozen in liquid nitrogen and lyophilized. The freeze-dried cotyledons were ground in a Wiley® mill using a 20-mesh screen, while embryonic axis tissue was ground by hand with a mortar and pestle. A 0.3- to 0.5-g dry tissue sample was used for each carbohydrate extraction. The tissue sample was placed in 10 ml of an 80-percent ethanol solution and heated in a 75 °C water bath for 1 hour. The sample was then filtered, rinsed with more of the ethanol solution, and evaporated to dryness. The evaporation flask

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

was rinsed with 10 ml of distilled water, and the water plus contents stirred with 1 g of Amberlite® MB-3 resin for 1 hour. This sample was then filtered, rinsed, and freeze-dried overnight. Phenyl-β-D-glucopyranoside was added as an internal standard. The dried sample was dissolved in 1 ml of trimethylsilylimidazole, heated in a 75 °C water bath for 30 minutes, blown to dryness, and then redissolved in 1 ml chloroform and stored until analysis. We performed analyses on a HP® 5890 gas chromatograph (GC) using a Supelco® SPB-5 capillary column (30 m by 0.25 mm ID by 0.25 film thickness). We made three to five extractions from each cotyledon sample and one to two from the embryonic axis sample, depending on amount of tissue available. We identified carbohydrates by comparing them with standards of pure sugars prepared in the same manner and injected onto the GC.

Invertase Analyses

We extracted invertase from cryostored cotyledon and embryo samples. After thawing and then remaining in a hydrated atmosphere for 15 minutes at room temperature, tissues were homogenized with a mortar and pestle in a small amount of an extraction buffer consisting of 200 mM Hepes/NaOH (pH 7.5), 3 mM Mg acetate, 5 mM DTT, 2-percent v/v glycerol, and 1-percent w/v insoluble PVP (Sung and others 1993, Xu and others 1989). Homogenate was placed in a test tube with a total of 1:5 or 1:3 (g fresh weight/ml) of the extraction buffer and incubated at room temperature for 15 minutes. The sample was then passed through one layer of Miracloth, fractioned with 70-percent $(NH_4)_2SO_4$, and centrifuged at 18,000 g for 20 minutes at 4 °C. The resulting pellet was resuspended in 5 ml of a resuspension buffer containing 10 mM Hepes/NaOH (pH 7.5), 2 mM DTT and 2 mM Mg acetate, and then desalted by passing through a Sephadex G-25 column. We assayed samples for acid and neutral invertase activity at pH 5.0 and 7.0, respectively, using a Milton Roy Spectronic 501 spectrophotometer set at 340 nm.

Fourier Transform Infrared (FT-IR) Spectroscopy

We placed thin slices of both white oak and cherrybark oak acorn cotyledon tissue and squashes of three to five embryonic axes between CaF_2 windows of a demountable transmission cell. A minimum of duplicate samples was analyzed. For each spectrum, 512 scans at 2/cm resolution were collected and averaged on a Nicolet 20 DXB spectrometer using a liquid nitrogen-cooled MCT-A detector. Single-beam spectra were ratioed against an open-beam background to yield transmission spectra. Attenuated total reflectance spectra were similarly recorded on thin slices of white oak embryonic axes and cotyledon tissue that were layered onto a 45° ZnSe crystal in an ARK sampling device (SpectraTech, Inc.). Instrument collection parameters were the same as for the transmission experiment. However, absorbance is the equivalent to log 1/R, where R = reflectance.

RESULTS AND DISCUSSION

Cherrybark oak acorn viability was sensitive to MC (fig. 1). If we allowed acorns to desiccate, germination declined rapidly in these recalcitrant seeds. Over the course of the experiments, MC in cherrybark oak dropped from 31.6 to 11.0 percent. Once MC was < 17 percent (day 4), viability declined rapidly. The MC of embryonic axes was always higher than that of the cotyledons.

White oak acorns, among the most recalcitrant of the Fagaceae, had a much higher initial MC than did cherrybark

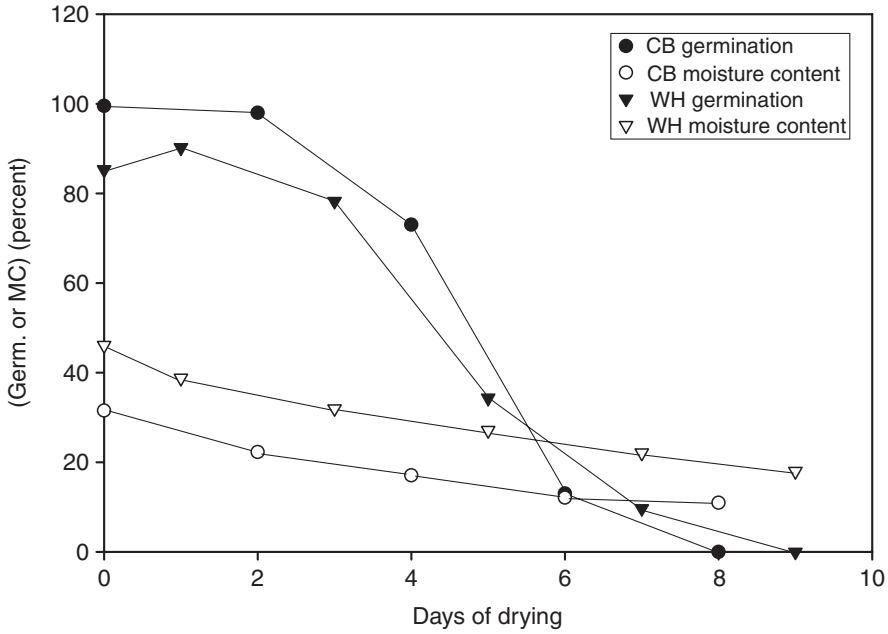

Figure 1—Germination and moisture content (MC) of white oak (WH) and cherrybark oak (CB) acorns desiccated over 8 to 10 days.

acorns, averaging 46 percent (fig. 1). MC dropped to 18 percent during the course of the experiments. Once MC reached 27 percent, viability was < 50 percent. Like cherrybark oak, the embryonic axes always had a higher MC than did the cotyledons.

We found phase changes in the membrane lipids in the embryonic axis and cotyledon membranes of both cherrybark oak and white oak, exhibited by peak shifts of the symmetric and asymmetric $-CH_2$ vibrations near 2850 and 2910/ cm (figs. 2 and 3). The transformation from liquid crystalline to gel phase can disrupt transport through membranes. The phase changes were reversible upon rehydration of the acorns up through day 5 of desiccation; after that time, reversibility was only partial, suggesting that damage to the membranes was permanent. Changes in membrane lipids in as few as 2 to 3 days of drying suggested that the physiological deterioration of acorns begins relatively soon after they are shed.

Cherrybark oak acorns have a high amount of storage lipids, evidenced by an ester carbonyl peak near 1740/cm (fig. 4). Unlike membrane lipids, the peak frequency of these lipids did not shift or change as acorns deteriorated, indicating little or no mobilization of lipids and transport from the cotyledons to the axes.

Unlike cherrybark oak, white oak acorns did not have a high amount of storage lipids, relying instead upon carbohydrates. The most prevalent carbohydrate in the acorns was sucrose, the amount of which fluctuated constantly as acorns desiccated (fig. 5). This fluctuation indicated that the metabolism of acorns was still very active despite the reduced MC and deteriorating state of the acorns. The

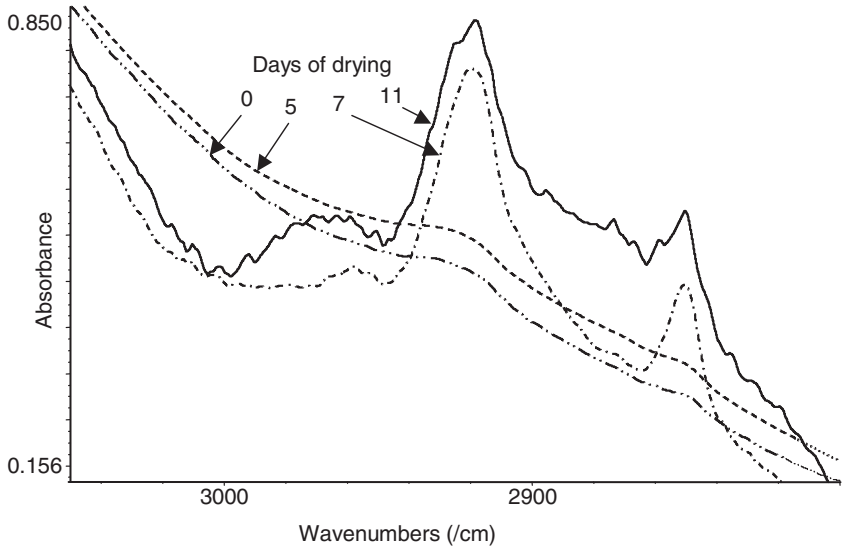

Figure 2—Membrane lipid vibrations in fresh (day 0) white oak embryonic axes and in those dried 5, 7, and 11 days. Peak frequencies occurred near 2850 and 2910/cm.

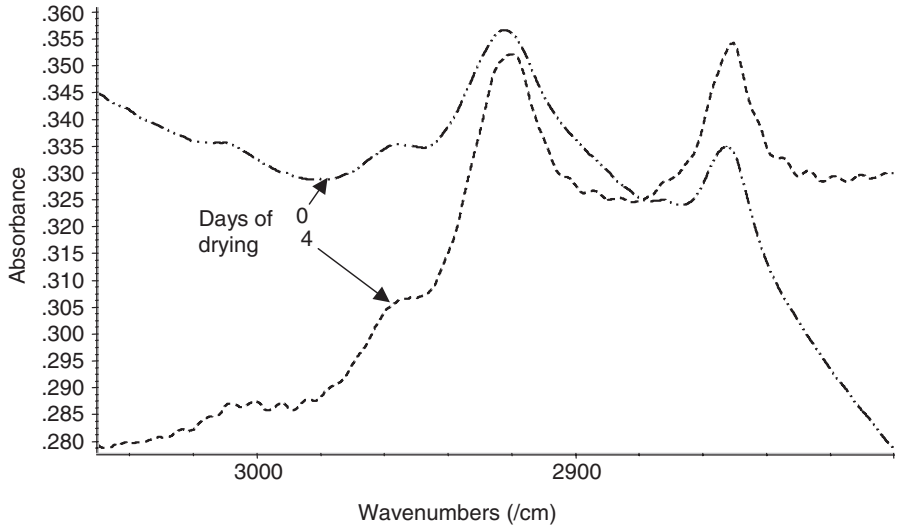

Figure 3—Membrane lipid vibrations in fresh (day 0) cherrybark oak embryonic axes and in those dried 4 days. Peak frequencies occurred near 2850 and 2910/cm.

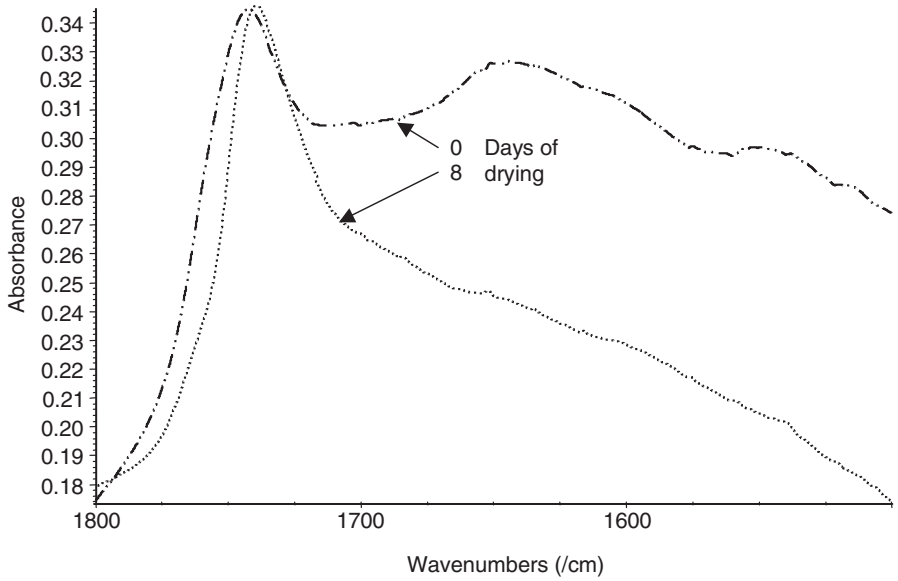

Figure 4—Storage lipid vibrations in fresh (day 0) cherrybark oak embryonic axes and in those dried 8 days. Peak height of the ester carbonyl vibration occurred near 1740/cm.

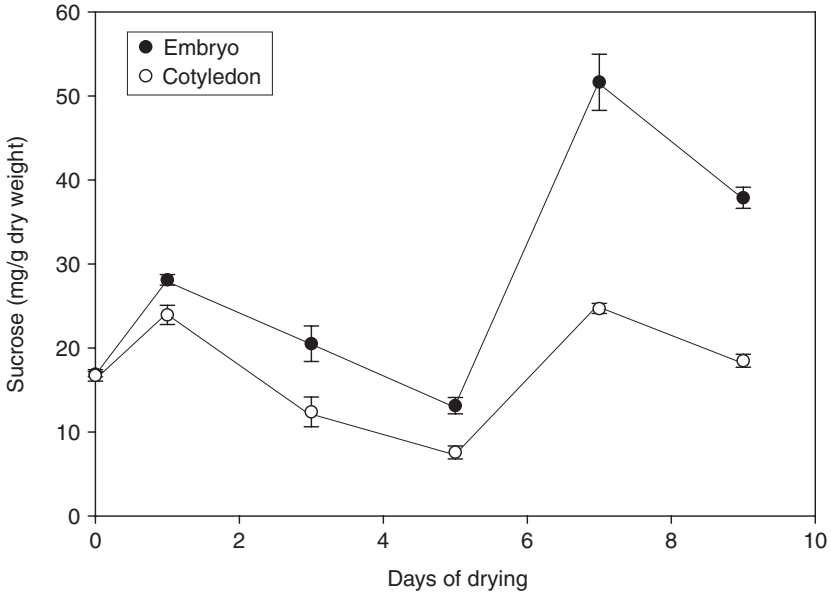

Figure 5-—Sucrose content (mg/g dry weight; ± one standard error) in desiccating white oak acorn embryonic axes and cotyledons.

fluctuating amounts of invertase found in the white oak acorns (table 1) enhanced this observation. Drops in MC did not terminate sucrose metabolism; there were significant changes in the sucrose content in both the embryonic axes and the cotyledons. The sucrose increase as tissue dried, while obviously not functioning to preserve seed viability, might function secondarily to protect membranes from desiccation damage and cells from collapse. The sucrose FT-IR peak at 1045/cm (fig. 6) confirmed the GC analyses.

In practical terms, these results advise against allowing acorns to remain too long exposed to the elements before collecting. The frequently hot, dry conditions during acorn fall in the South may lead to serious viability losses. In the laboratory, under ideal conditions, white oak acorn viability dropped from 90.1 to 78.3 percent after only 3 days of drying. Cherrybark oak acorn viability dropped from 98.0 to 73.0 percent after 4 days. It is doubtful that germination would be as high in the field; it is also possible that seedlings grown from stressed acorns might exhibit reduced growth and vigor.

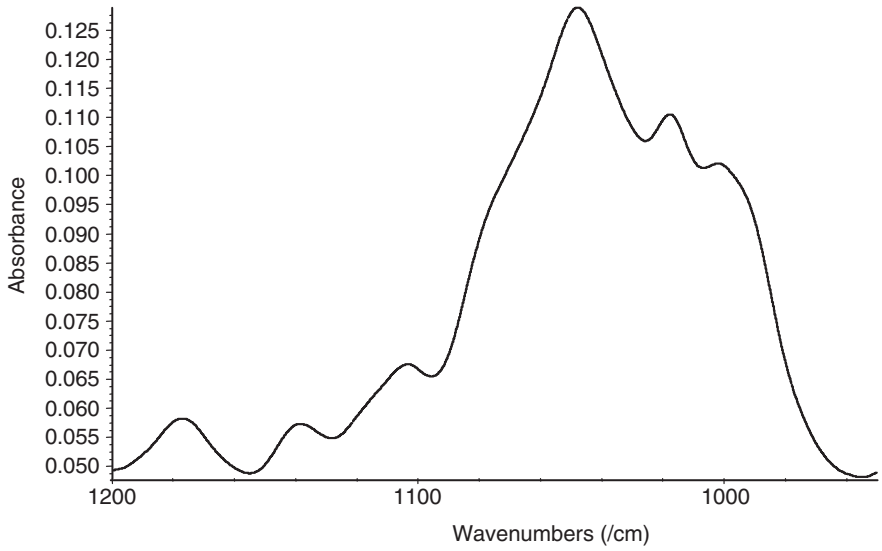

Figure 6—Attenuated total reflectance spectrum of carbohydrates in white oak acorn embryonic axes.

Table 1—Invertase activity in white oak acorn cotyledons

Drying	Invertase activity[a]	Hydrolyzing potential[b]
days		
0	847	289.7
1	397	135.8
3	709	242.5
5	492	168.3
7	327	111.8
9	870	297.5

[a] Units of invertase in 1 g of fresh cotyledon tissue; where one unit will hydrolyze 1 µmole of sucrose to invert sugar per minute at 55 °C.
[b] µmoles of sucrose that can be converted to invert sugar by the invertase present in 1 g of fresh tissue.

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DISTRIBUTION OF MATURE CONES, CONELETS, AND OLD CONES IN SHORTLEAF PINE-OAK STANDS AFTER AN UNEVEN-AGED REGENERATION CUT

Kenneth J. Grayson, Robert F. Wittwer, and Michael G. Shelton[1]

Abstract—Sixteen shortleaf pine trees were felled in a stand 10 years after an uneven-aged regeneration cut reduced pine basal area to 60 square feet per acre and hardwoods were controlled. Sixteen unreleased trees in an adjacent uncut pine-hardwood stand (120 square feet per acre) were felled for comparison. Sample trees were selected from four 2-inch d.b.h. classes (11, 13, 15, and 17 inch) and tree crowns were divided into four positions (upper south, upper north, lower south, and lower north). The 15- and 17-inch released trees produced significantly more mature cones than unreleased trees in the same classes (by four times) and released trees in smaller classes (by four times). Cone production for unreleased trees did not differ among diameter classes. Cone production by crown position ranked: lower north = lower south < upper north < upper south. The lower north position produced significantly fewer conelets than other positions. Released trees retained more older cones than unreleased trees, and older cones were significantly correlated with both mature cones and conelets.

INTRODUCTION

Successful natural regeneration of shortleaf pine depends upon production of adequate crops of viable seeds along with appropriate seedbed conditions (Shelton 1995). Natural stands of shortleaf pine have highly variable seed crops because of many biotic and abiotic factors which reduce the reliability of natural regeneration methods in these stands (Wittwer and Shelton 1992). An adequate seed crop consists of 80 to 250 thousand sound seeds per acre (Baker 1982, Haney 1962). Awareness of the amount of seeds required to naturally regenerate forests has stimulated interest in the cone producing ability of trees in natural stands (Thorbjornsen 1960). Five factors contribute to flower bud initiation: induction hormones, soil moisture, light conditions, nutrient relationships, and temperature. Light, nutrients, and moisture can be manipulated to increase seed production through thinning (Barnett and Haugen 1995). For example, removal of all trees within 30 feet of shortleaf pine seed trees doubled cone production per tree and significantly increased the number of sound seeds per cone (Yocom 1971).

Little is known about the distribution of cones within the crowns of conifers (Mattson 1979). Lyons (1956) found seed yields varied between cones of red pine (*Pinus resinosa* Ait.) trees, and there is a danger of not estimating seed production correctly if cones are sampled without regard to their location in the crown. Fatzinger and others (1980) found the majority of southern pine strobili were produced in the upper crown on the east and south sides of seed orchard trees. A study of slash pine (*Pinus elliottii* Engelm.) found the majority of cones occurred on the east side of the crown (Smith and Stanley 1969).

Our study was conducted to determine the effects of an uneven-aged regeneration cut on the distribution of mature cones, clusters of mature cones, conelets (immature cones), and older cones within the crowns of released and unreleased shortleaf pine trees by d.b.h. class. A better understanding of these relationships will be useful for selecting trees to retain for seed production and will provide indicators for forecasting future seed crops.

STUDY AREA

The study area was located in the Ouachita National Forest on the Winona Ranger District, Perry County, AR. Before implementation of uneven-aged management, the stand was irregularly aged with a uniform canopy dominated by shortleaf pine with mixed hardwoods in the mid to lower canopy. Sixteen 0.5-acre plots were established and were harvested from December 1988 to March 1989 to reduce the overstory pine basal area to 60 square feet per acre (Shelton and Murphy 1997). Plots received one of three residual hardwood basal area treatments (0, 15, and 30 square feet per acre). However, only the four plots with complete hardwood control were used for this study. Each of the 0.5-acre plots was surrounded by a 58 foot buffer zone receiving the same treatment. Shortleaf pine site index averaged 57 feet at 50 years. Shelton and Murphy (1997) have given a more detailed description of the study area.

METHODS

Sample Tree Selection

Sixteen released trees were selected from the buffer zones of the four treated plots (60 square feet per acre of pine basal area with no hardwoods). Sixteen unreleased trees were selected from the adjacent unharvested pine-hardwood mixed forest (120 square feet per acre of total basal area with two-thirds in pine and the remainder in hardwoods). Sample trees were randomly selected from 2-inch d.b.h. classes (11, 13, 15, and 17 inch). Sample trees with malformed crowns were excluded from selection. Sample trees were measured for height, d.b.h., crown length, crown width, and 5-year radial growth increment at stump height. A cone rating procedure described by Shelton and Wittwer (1995) was used to give each sample tree a cone density class based on cone spacing, occurrence of cones

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

in clusters, and distribution of cones within the crown. The observer stood one to two tree heights away from the tree with the sun to their back and viewed the tree crown with 7-power binoculars. The same observer evaluated each sample tree before felling and gave a cone rating of 0 for few (< 10 cones), 1 for average (10-80 cones), and 2 for good (> 80 cones) as viewed from a single position. After felling sample trees, basal area was determined with a 10-factor prism at a point centered over the stump.

Trees were felled during a 2-week period in the middle of October 1998 when cones were mature. Selected trees were marked with paint on the magnetic north and south sides of the bole so the proper crown positions could be established. After felling, each crown was measured for total length and divided into two equal upper and lower halves. The crown was further divided by north and south facing branches to form four crown positions: lower north, lower south, upper north, and upper south. Branches ($\geq$ 1.0 inch basal diameter) were assigned to a particular crown position based on their origin at the main stem.

The four crown positions and four d.b.h. classes were considered treatments split between the released and unreleased treatments with four replications (four blocks) of each treatment. This resulted in a two by four by four factorial, split-split plot randomized, complete block design. Two branches from each crown position for each tree were randomly selected for evaluation of mature cones, conelets, and older cones. Mature cones were counted by the number of cones present in a cluster (i.e., cones occurring at the same location on the branch). We defined older cones as having 50 percent or more of their scales intact and still attached to branches. The older cone counts were indicators of past production through at least 4 years. Mature cones were counted from the remaining branches from each crown position.

Data Analysis

Mean values were calculated for all reproductive structures on a per crown position basis. Reproductive structure counts for the two sample branches per crown position were averaged and then multiplied by the number of branches in each crown position to estimate reproductive structures within each crown position. The number of mature cones per crown position was determined by a complete count, but an estimated value was also calculated for comparison.

The MIXED procedure from SAS Institute (1997) was used for analysis of variance for the split-split plot arranged in a randomized complete block design to make inferences about cone distribution by crown position, d.b.h. class, and stand density (main unit treatment). All variables were considered fixed for the mixed model except blocks. Multiple mean comparisons (Fishers Least Significant Difference) were attained by using the LSMEANS statement and DIFF and SLICE options (SAS Institute 1997). The SLICE option tests for simple effects; if the interaction of factors A*B is significant, the effect of A for each level of B is tested. In addition, correlation analysis was used to determine possible relationships between cone variables. Significance for all statistical tests was accepted at $\alpha = 0.05$.

RESULTS AND DISCUSSION

Sample Tree Characteristics

Age of unreleased trees ranged from 60 to 110 years, averaging 78 years, while released trees ranged from 54 to 88 years and averaged 76 years. Sample trees averaged 14.0 inches d.b.h. for unreleased trees and 14.2 inches for released trees. The height of unreleased trees averaged 66 feet compared to 67 feet for released trees. Crown length and width for the released trees averaged 33 and 27 feet, respectfully; this was about 3 feet more for each dimension than the unreleased trees. Released trees also averaged 35 branches per tree compared to 31 branches for the unreleased trees. As one might expect, the last 5 years of radial growth for the released trees was 0.2 inch greater than that for unreleased trees.

Mature Cone Production

Released trees produced an average of 1,179 mature cones compared to 422 mature cones for unreleased trees. For all 32 sample trees, mature cone production ranged from 17 to 3,175 cones per tree. Bower and Smith (1961) compared mature cone production between five pairs of partially girdled and non-girdled shortleaf pine trees showing evidence of past cone production and found the partially girdled trees produced an average of 750 cones per tree compared to 185 cones for the non-girdled trees. Coulson and Franklin (1970) evaluated 21 shortleaf pine trees for cone damage by populations of *Dioryctria* spp. in Georgia and reported cone production ranged from 56 to 699 cones per tree with an average of 352 cones. Cone production appears to vary greatly from year to year and between trees for any given year.

A study estimating seed quantity and quality of shortleaf pine cones in the Ouachita Mountains found the average number of sound seed per cone was 14.5 in a seed-tree stand and 17.5 in a single-tree-selection stand (Wittwer and others 1997). Their results indicated that approximately 20 sound seeds per cone could reasonably be expected for shortleaf pine. If the average released trees in the present study produced 20 sound seeds per cone, approximately 23,600 sound seeds per tree would have been produced. The average unreleased tree would have produced approximately 8,400 sound seeds.

Mature Cone Distribution

A significant interaction occurred between stand density (released versus unreleased) and tree d.b.h. class for mature cone production. Released trees in the 15- and 17-inch d.b.h. classes produced significantly more cones than smaller trees (fig. 1). However, significance was found only in these d.b.h. classes, and no significant difference occurred for mature cones by d.b.h. class for the unreleased trees. These results demonstrate the importance of retaining the larger trees within the stand to maximize seed production under similar conditions as in this study.

A significant interaction occurred between stand density and crown position for the distribution of mature cones within the crown. Cone production by crown position was ranked as follows: lower north = lower south < upper north < upper south (fig. 2). Upper crown positions produced significantly more cones than lower crown positions for

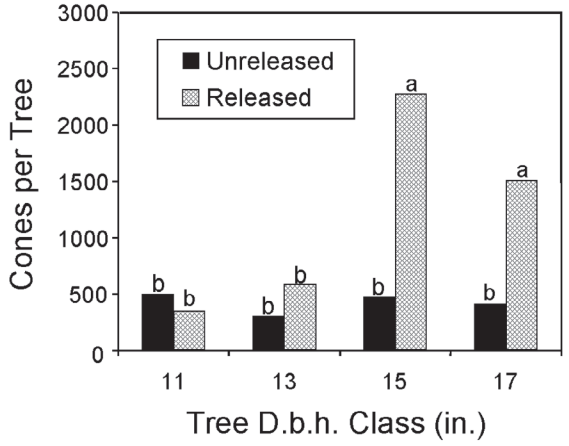

Figure 1—Effects of release and tree d.b.h. on the number of mature cones in shortleaf pine trees. Bars with the same letter are not significantly different at $\alpha = 0.05$.

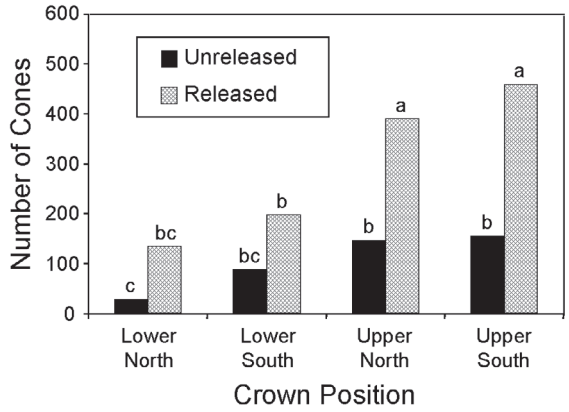

Figure 2—Effects of release and crown position on the number of mature cones in shortleaf pine trees. Bars with the same letter are not significantly different at $\alpha = 0.05$.

released trees. However, this trend was not as strong for the unreleased trees, and only the lower north crown position was significantly different from the upper crown positions. The distribution of cones within the crown is probably associated with the vigor and age of branches. A similar distribution pattern was reported for young, open-grown Douglas-fir trees; branches on the upper and middle south side of the crown produced the greatest number of cones (Winjum and Johnson 1964). Hard (1964) reported a relationship between branch age and fertility for red pine, where older branches produced more male flowers, and younger branches produced more mature cones. For species with wind-disseminated seeds, having most of the cones located in the upper portion of the crown would maximize seed dispersal and the opening of cones through drying.

Conelet Production and Distribution

Analysis of variance indicated no significant difference in conelet production between released and unreleased trees. The average released tree produced 233 conelets compared to 110 conelets for the average unreleased trees. A lack of significant difference between these two means suggests that during poor cone crops variability increases and differences becomes less pronounced. This level of conelet production suggests that next year's mature cone crop will only be 20 percent of the current year's crop. This shows the highly variable nature of shortleaf seed production in the Ouachita Mountains. Analysis of variance indicated a significant effect of crown position with only the lower north position varying significantly from the other crown positions (fig. 3).

Older Cone Distribution

Analysis of variance revealed significant effects for stand density, crown position, and tree d.b.h. class. Older cones on released trees differed significantly from unreleased trees, averaging 2,419 and 631 cones, respectively. The 15- and 17-inch d.b.h. classes for released and unreleased trees retained significantly more old cones than smaller trees (fig. 4). Older cones also differed by crown position; the upper crown positions were significantly greater than the lower north crown position, but not the lower south position. These findings were very similar to the mature

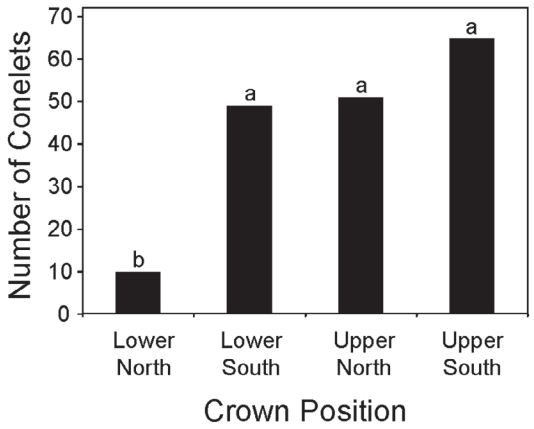

Figure 3—Effects of crown position on the number of conelets in shortleaf pine trees. Bars with the same letter are not significantly different at $\alpha = 0.05$.

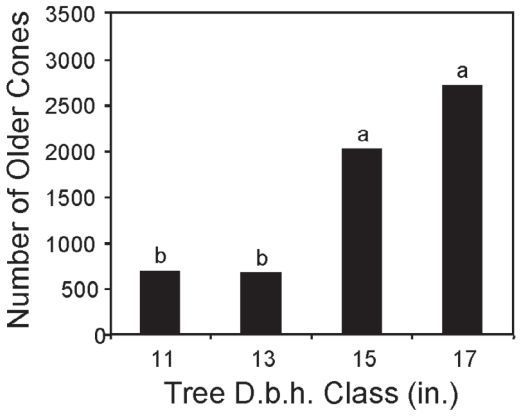

Figure 4—Effects of tree d.b.h. on the number of older cones in shortleaf pine trees. Bars with the same letter are not significantly different at $\alpha = 0.05$.

cone production trend with more cone production occurring in the upper crown positions. Wenger (1953) suggested that the most reliable way to select fruitful trees was to choose larger trees that show evidence of past production by the presence of older cones. If d.b.h. was the same for two trees, then the tree with the greatest number of older cones should be selected. Our study supported this conclusion.

Correlation Analysis

The estimate of mature cones per tree was highly correlated with the actual total count of mature cones per tree (r = +0.85, P = 0.0001), suggesting that the cone counts on the eight sample branches per tree were adequate to estimate total cones per tree. This represents a 24 percent sample since the average sample tree had 33 branches.

Mature cone production was significantly correlated with the number of two-, three- and four-cone clusters (r = +0.92, +0.87, and +0.65, respectively; P = 0.0001 in all cases). This suggests that the presence of multiple-cone clusters could be used as an indicator of the total production of mature cones. The correlation coefficient between older cones and mature cones was +0.71 (P = 0.0001), and the correlation between older cones and conelets was +0.77 (P= 0.0001). This suggests that the older cones are a good indicator of the tree's potential for future cone production.

For sample tree variables, mature cone production was significantly correlated with crown length (r = +0.36, P = 0.04), stand basal area at the sample tree's location (r = -0.44, P = 0.01), 5-year radial growth (r = +0.38, P = 0.03), and cone rating (r = +0.80, P = 0.0001). Thus, the cone rating method of Shelton and Wittwer (1995) was the most promising variable for estimating mature cones per tree.

CONCLUSIONS

The average released tree produced almost three times the number of mature cones of the average unreleased tree. The uneven-aged regeneration cut had its greatest impact on released trees 14 inches d.b.h. or greater, with most of the increase in cone production occurring in the upper crown positions. Cone production for unreleased trees did not differ significantly by tree d.b.h. class. The only significant difference for unreleased trees occurred among crown positions, with the upper crown positions producing significantly more cones than the lower north position. Results suggest that under similar stand conditions, released trees at least 14 inches d.b.h. should be selected to maximize seed production.

The presence of multiple-cone clusters was highly correlated with total cone production. Cone clusters were also significantly more abundant in the upper crown positions. Clusters of cones in upper crown positions should be a good indicator of potential seed production.

Conelet production differed significantly only by crown position, with the lower north position having significantly fewer conelets than other positions. Conelet production was poorly correlated with mature cone production. This demonstrates the sporadic pattern of shortleaf pine cone crops in the Ouachita Mountains. Results for conelet distribution found in this study suggest that during poor cone crops, the differences among tree d.b.h. classes are less noticeable.

Older cones differed significantly between released and unreleased trees, with released trees having nearly four times the number of older cones as unreleased trees. Older cones also differed significantly among tree d.b.h. classes, with the 15 and 17 inch trees having significantly more older cones than smaller trees. The lower north position had significantly fewer older cones than other crown positions. Older cones were significantly correlated with both mature cones and conelets, suggesting that the presence of older cones is a good indicator of future cone production and could be used to select fruitful trees for retention.

The cone density rating appeared to be a promising method for successfully predicting the seed production of individual trees. According to Shelton and Wittwer (1995), the cone density rating can be applied with a maximum lead time of about 5 months prior to seed fall. Although south crown positions produced more cones than north positions, the effects were minor and often not statistically significant. Thus, this factor can probably be ignored in making cone counts or ratings.

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EFFECTS OF LIGHT REGIMES ON THE BIOMASS AND MORPHOLOGICAL CHARACTERISTICS OF 2-YEAR-OLD CHERRYBARK OAK SEEDLINGS

Yanfei Guo and Michael G. Shelton[1]

Abstract—We used modified shadehouses to simulate the complex light conditions within forest openings and tested the effects of time of direct light exposure, the ratio of direct light to day length, and daily photosynthetically active radiation on aboveground biomass and morphological characteristics of 2-year-old cherrybark oak (*Quercus pagoda* Raf.) seedlings. The five treatments represented the time of exposure to direct sunlight: NO, NOON, MORNING, AFTERNOON, and FULL. At the end of the second growing season, aboveground biomass was not statistically different among the treatments receiving direct sunlight but was significantly lower for the NO treatment. The NO seedlings had the lowest foliage density (leaf number per unit of stem height), while the FULL seedlings had the greatest foliage density. The mean weight of individual leaves did not differ among the light regimes, but individual leaf area in the NO treatment was 65 percent greater than that in the FULL treatment. Results of this study indicate that cherrybark oak seedlings adapt their physiological and morphological features to the prevailing light regime.

INTRODUCTION

Oak seedlings are shade intolerant to intermediately intolerant (Smith 1992) and do not grow well under a closed forest canopy (Lorimer and others 1994). Once advanced oak reproduction is established, seedlings need adequate light to grow faster than competing vegetation (Bey 1964; Crow 1988; Johnson 1979; Minckler 1957; Sander 1972). Light conditions within a stand can be improved by creating openings or reducing stand density through natural disturbance or artificial removal of overstory and/or midstory trees. Considerable research has been conducted relating forest opening size or residual overstory basal area to oak seedling growth (Minckler and Woerheide 1965; Sander and Clark 1971; Smith 1980, 1981). However, quantifying the complex light conditions occurring within stands and relating them to seedling growth are difficult. Light conditions in the field can be complex; direct and partial sunlight may reach seedlings during certain times of a day, but seedlings may be fully shaded at other times. A complex light regime with fluctuating periods of direct and indirect sunlight is difficult to mimic but may strongly affect seedling establishment and growth.

Light is important for oak seedlings because it affects rates of photosynthesis. Under a closed canopy, Hanson (1986) found negative CO_2 assimilation for northern red oak seedlings. Lorimer and others (1994) found that 70 percent of planted white oak (*Quercus alba* L.) and northern red oak (*Q. rubra* L.) seedlings died within 5 years under a closed canopy, and the surviving seedlings showed a net decrease in total height. Oak seedlings do not grow well under full shade because they spend half of produced photosynthates for respiration (Dickson and others 1990). Northern red oak seedlings had similar daily CO_2 assimilation in both open areas and in sunflecks during clear days (Hanson 1986). Apparently, adequate amounts of direct sunlight exposure or photosynthetically active radiation (PAR) are important for oak seedling growth. Gardiner and Hodges (1998) reported approximately 6 times more biomass with 53 percent of the total available PAR than with 8 percent of total PAR for 2-year-old cherrybark oak (*Q. pagoda* Raf.) seedlings. On the other hand, during certain stages of seedling development, excessive exposure to sunlight may damage the photosynthetic apparatus thereby reducing or inhibiting photosynthesis (Powles 1984).

We hypothesized that timing and amount of daily direct sunlight exposure, amount of PAR, and ratio of direct sunlight to total sunlight would affect the growth and characteristics of cherrybark oak seedlings. To test the hypotheses, we used a nontraditional type of shadehouse to simulate the light conditions occurring within small forest openings. Each shadehouse had sections that had no shade cloth on top, which allowed direct sunlight to reach seedlings during different times of day. Applying methods of Marquis (1965) and Satterlund (1983), we calculated the length of time seedlings were exposed to direct sunlight and tested the effect of light regimes on aboveground biomass and morphological characteristics of 2-year-old cherrybark oak seedlings. The effect of light regimes on periodic height and diameter growth was reported earlier (Guo and others 2001).

METHODS

The study site was located in Drew County, Arkansas (91° 50' W and 33° 37' N) in the west Gulf Coastal Plain. The soil is an Amy silt loam (Typic Ochraquults). Site index for cherrybark oak is about 26 m at age 50. Before the study was established, the area was an open field, but the native vegetation of the site is classified as mixed pines and hardwoods (Larance and others 1976). Annual precipitation averages 134 cm, with most occurring in the winter and early spring.

The study was a split plot with a completely randomized block layout and three replicates. The main plot was the regimes of direct sunlight, and subplot was parent trees. With the shadehouses oriented toward north, five light

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

regimes were created based on when direct sunlight occurred: mostly in the morning (MORNING), around noon (NOON), mostly in the afternoon (AFTERNOON), all day (FULL), and at no time (NO). The treatments were intended to represent the light conditions occurring within a small forest opening: FULL at the center of a large opening, NO at the south end, MORNING at the western edge, AFTERNOON at the eastern edge, and NOON at the center and northern edge of smaller openings.

The dimensions of the shadehouses for the NOON treatment were 2.4 x 3.7 x 2.4 m, while the dimensions for the NO treatment were 2.4 x 2.4 x 2.4 m (Guo and others 2001). Shade for the MORNING and AFTERNOON treatments came from the vertical walls of the NOON treatment. All shade cloth provided 20 percent of full sunlight. The shadehouse for the NO treatment had shade cloth on the top and all sides except for the lower half of the north side. The NOON treatment only had vertically-oriented shade cloth on the north, east, and west side.

Acorns from four open-pollinated cherrybark oak trees in Drew County, AR were collected in November 1996, float tested, and stored in a refrigerator at 4 °C. Acorns were stratified for 60 days and sown in a soil-vermiculite mixture in February 1997. Seedlings were grown for 2 months in a greenhouse before field planting in April 1997. Six seedlings from each parent tree were planted in 0.9- x 1.5-m beds in each main-plot treatment. Seedlings were planted with a 0.3- x 0.3-m spacing and a 4 row x 6 column arrangement with parent trees randomized within a row. A total of 24 seedlings was planted in each plot for a total of 360 seedlings in the study. During the first month after planting, dead seedlings, averaging six seedlings per bed, were replaced by seedlings of the same parent tree. Replanting was mainly due to a severe storm in early May with high wind, which damaged shoots, and root damage caused by burrowing crawfish. Replanted seedlings did not differ ($P > 0.05$) from non-replanted seedlings in height and root-collar diameter.

A mulch of foliar litter from a mixed hardwood stand was used to retard herbaceous plant competition within the beds, and beds were periodically hand-weeded. Herbaceous vegetation outside of the beds was periodically controlled with a foliar-applied herbicide. Seedling beds were irrigated to field capacity during periods of low summer rainfall.

For the partially shaded treatments, the length of time each planting space was in direct sunlight at ground level was calculated for each day by tracking the shadows cast by the shadehouse's walls. Solar declination was calculated from formula given by Satterlund (1983), and shadow lengths during each day were calculated from formula provided by Marquis (1965) and Satterlund (1983). Day lengths, the time between sunrise and sunset, were obtained from the Time Service Department (U.S. Naval Observatory, Washington, DC) for each day of the second growing season. The ratio of direct sunlight to day length (the direct-sunlight ratio) was calculated for each day of a measurement period and then averaged for the second growing season. A LI-190SA quantum sensor (LI-COR, Inc. Lincoln, Nebraska, USA) was installed in each treatment of one shadehouse. The calibrated sensors allowed determining mean PAR for each treatment. PAR was automatically recorded by a LI-1000 (LI-COR, Inc. Lincoln, Nebraska, USA) data logger at a 15 minute interval for 2 days a week during the second growing season.

On November 5 and 6, 1998, foliage, branches, and stems of seedlings were harvested by parent trees within a plot after counting the number of surviving seedlings. We randomly collected a subsample of 20 leaves from each parent to determine leaf area using a LI-COR 3100 Area Meter (LI-COR Inc. Nebraska, USA). Biomass samples were dried in a force-draft oven at 75 °C until constant weights were obtained. The 20-leaf subsamples were dried and weighed separately.

The average number of leaves for the seedlings of a parent tree was calculated by dividing foliar biomass (corrected for the 20-leaf subsample) by the average weight of individual leaves determined from the subsample. To obtain an expression of seedling morphology, we calculated foliage density (leaf number m^{-1}) as the ratio of leaf number to seedling height. A similar expression was calculated for foliage area density ($m^2\ m^{-1}$), which was the ratio of leaf area of seedlings to their height. All seedling characteristics were analyzed by General Linear Procedure of SAS (1990). Means were separated by the Ryan-Einot-Gabriel-Welsch multiple range test at $\alpha = 0.05$. Regression was used to relate foliage density or foliage area density to seasonal mean daily PAR or direct sunlight ratio using a simple linear model. All reported regression coefficients differed from zero at $\alpha \leq 0.05$.

RESULTS AND DISCUSSION

Light Regimes

Seasonal mean daily PAR (mol m^{-2} per day) was computed by adding all the measurements for a day and calculating the mean daily PAR. Mean daily PAR varied among the light regimes, ranging from 6.6-10.9 mol m^{-2} per day for NO, 20.0-24.3 mol m^{-2} per day for NOON, 25.2-34.7 mol m^{-2} per day for MORNING, 28.2-37.1 mol m^{-2} per day for AFTERNOON, and 36.3-45.8 mol m^{-2} per day for FULL. Direct sunlight exposure at ground level in the NOON treatment ranged from 3.6 hours per day in May to 2.7 hours per day in October. MORNING and AFTERNOON treatments averaged 8.5 hours per day in May and 6.9 hours per day in October. For the FULL treatment, day length varied from 13.6 hours in May to 11.2 hours in October. Exposure to direct sunlight increased as seedlings grew taller because the distance between the top of the shadehouse and the seedling's height diminished. In May for example, direct sunlight in the NOON treatment increased from 3.6 hours per day at ground level to 7.3 hours per day at 1.5 m above ground. Direct sunlight in the MORNING treatment increased from 8.5 hours per day at ground level to 10.3 hours per day at 1.5 m above ground in May. The pattern in the AFTERNOON treatment was similar to that of the MORNING treatment.

Aboveground Biomass

Mean foliar biomass of the NO seedlings was significantly smaller than that of the other treatments, and there was no statistical difference among the remaining treatments (fig. 1).

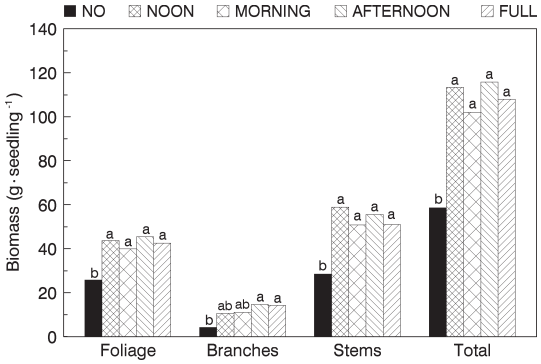

Figure 1—Effect of light regimes on foliage, branch, stem, and total aboveground biomass of cherrybark oak seedlings at the end of the second growing season. Bars with the same letter in the same cluster are not significantly different at $\alpha = 0.05$.

The mean foliar biomass for the NO seedlings was 26 g, compared to 40-46 g for seedlings in the other treatments. Mean branch and stem biomass had similar patterns to that of foliage, except that mean branch biomass of the NO seedlings did not differ from those with the NOON and MORNING treatments. However, mean branch biomass in the NOON and MORNING treatments was more than twice the biomass of the NO seedlings (11 versus 4 g). Total biomass was similarly affected by light regimes. The mean total biomass of the NO seedlings was 59 g, which was significantly smaller than that of other treatments (102-116 g) (fig. 1). Significant variation occurred among seedlings from the parent trees, but parent trees did not significantly interact with light regimes. Seedlings with the greatest total biomass (Parent 4) exceeded those with the least (Parent 2) by 63 percent.

The percentage of total biomass in stems did not differ among treatments. Although the NO treatment had both the lowest foliage and total biomass, the percentage of total biomass in foliage for the NO treatment was significantly greater than the percentage for other treatments (fig. 2). No difference was found among the treatments receiving direct sunlight. In contrast, the percentage of total biomass in branches for the NO treatment was the lowest observed and was significantly different from the

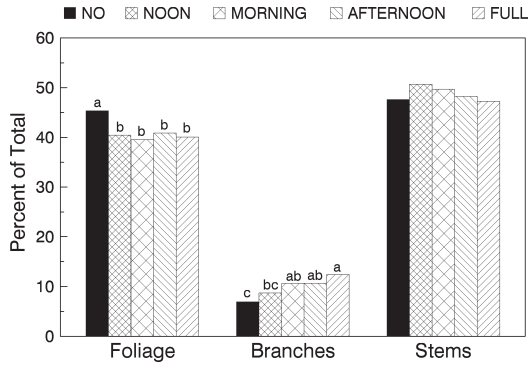

Figure 2—Effect of light regimes on the percentage distribution of total α aboveground biomass among foliage, branches, and stems of cherrybark oak seedlings at the end of the second growing season. Bars with the same letter or no letter in the same cluster are not significantly different at $\alpha = 0.05$.

FULL treatment but not the NOON, MORNING, and AFTERNOON treatments. This difference in biomass allocation appeared to be an adaptation to the shade. Smith (2000) stated that shade avoidance is a developmental response, which collectively allows plants to maintain photosynthetic structure in limited light conditions.

Morphological Characteristics

The low foliar biomass of the NO treatment was due to fewer leaves on the seedlings, because no significant differences occurred among light regimes for the mean weight of individual leaves (table 1). Leaf weights only ranged between 0.56 to 0.63 g leaf^{-1}. In contrast, leaf area varied significantly among the treatments and strongly reflected the amount of direct sunlight a treatment received. Leaves in the NO treatment had 65 percent more area per leaf than those in the FULL treatment. Specific leaf area ranged from a minimum of 96 cm^2 g^{-1} in the FULL treatment to a maximum of 142 cm^2 g^{-1} in the NO treatment; these values and the pattern of variation were consistent with those compiled for a wide variety of different tree species by Shelton and Switzer (1984). In addition, shade leaves usually develop bigger chloroplast and are richer in chlorophyll content than sun leaves (Boardman 1977).

Foliage density averaged 39, 52, 57, 61, and 69 leaves m^{-1} in NO, NOON, MORNING, AFTERNOON, and FULL treatments, respectively. Foliage density was linearly related to seasonal mean daily PAR (r = +0.81) and to seasonal mean direct sunlight ratio (r = +0.79) (fig. 3). On the other hand, foliage area density was not significantly affected by light regimes, with values only ranging from 0.34 to 0.36 m^2 m^{-1}. This phenomenon was likely caused by an increase in individual leaf area as shading increased.

CONCLUSIONS

Light conditions were important for the early growth of cherrybark oak seedlings. A daily direct sunlight exposure of 3-4 hours on the forest floor and 20 percent of the full sunlight in the remaining time resulted in the same aboveground biomass as longer exposures. Without any direct sunlight and about 23 percent of the total daily PAR, biomass was significantly reduced. Some exposure to direct

Table 1—Effect of light regime on the mean properties of individual leaves of cherrybark oak seedlings at the end of the second growing season

Light regimes	Wgt.	Area	Specific leaf area
	g	*cm²*	*cm² g⁻¹*
No	0.63[a]	89a	142a
Noon	0.60	68b	116b
Morning	0.58	60bc	103c
Afternoon	0.59	63bc	106c
Full	0.56	54c	96c

Means are based on four subsamples of 20 randomly selected leaves within each bed.

[a] Means of a column with the same letter or no letter are not significantly different at α = 0.05.

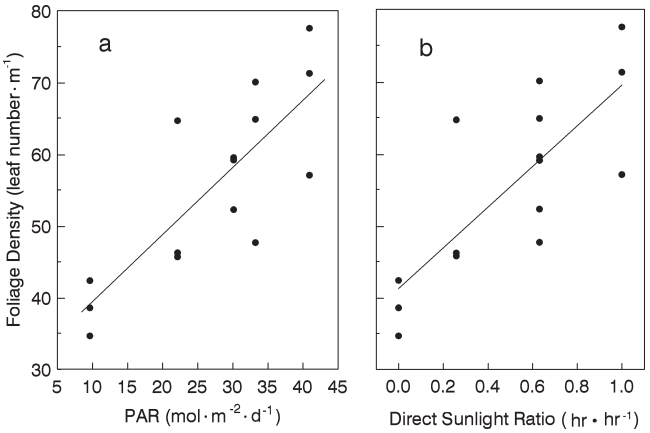

Figure 3—Relationship between foliage density of cherrybark seedlings at the end of second growing season and (a) the seasonal mean daily PAR and (b) the mean direct sunlight ratio. For mean seasonal daily PAR: Y = 30.07 + 0.935X; r^2 = 0.66. For direct sunlight ratio: Y = 41.22 + 28.26X; r^2 = 0.62.

sunlight seemed to be important for maximum seedling development. The implication of this finding is that if competition is controlled, proper size of forest openings or overstory coverage is important for adequate direct sunlight exposure of the seedlings. In response to different light regimes, seedlings developed different foliar densities and morphologies. Foliage density was significantly greater for the FULL seedlings than for the NO and NOON seedlings. There was a positive linear relationship between foliage density and direct sunlight ratio and PAR. High foliage density would have provided more mutual shading for seedlings in the FULL treatment, which might have been beneficial in avoiding excess light. However, foliage area distribution did not differ greatly among the treatments because of the increased area of individual leaves as shading increased. Finally, selection of maternal trees for acorn collection is important for producing seedlings for planting. Results from our study showed a difference in biomass of up to 63 percent resulted from seedlings that originated from different parent trees.

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ESTIMATING LEAF NITROGEN OF EASTERN COTTONWOOD TREES WITH A CHLOROPHYLL METER

Benoit Moreau, Emile S. Gardiner, John A. Stanturf, and Ronald K. Fisher[1]

Abstract—The utility of the SPAD-502 chlorophyll meter for nondestructive and rapid field determination of leaf nitrogen (N) has been demonstrated in agricultural crops, but this technology has not yet been extended to woody crop applications. Upper canopy leaves from a 5-year-old plantation of two eastern cottonwood (*Populus deltoides* Bartr. ex Marsh.) clones established on a former agricultural field were collected to determine the relationship between SPAD values and foliar N. The two clones, Stoneville-66 and Stoneville-75, differed in chlorophyll concentrations but had similar leaf N concentrations; relationships between N, chlorophyll, and SPAD values were not influenced by clone. Total chlorophyll was closely associated with total N concentration (mass basis) and content (area basis) (r^2 = 0.76 and 0.66, respectively), and SPAD values accurately predicted total N concentration and content (r^2 = 0.74 and 0.67, respectively). Results from this study indicate that SPAD-502 values < 32 signify a N deficiency level severe enough to limit the productivity of eastern cottonwood. The SPAD-502 chlorophyll meter shows promise as a tool for rapid field estimation of leaf N concentration or content in eastern cottonwood trees. Our findings support the development of this technology for use in eastern cottonwood or other short-rotation woody crop applications. Future investigations should be expanded to examine other eastern cottonwood clones on other site types and to standardize sampling protocols for various stages of tree phenology.

INTRODUCTION

Previous research has demonstrated the utility of the SPAD-502 chlorophyll meter (Soil-Plant Analysis Development Section, Minolta Corp., Osaka, Japan) for nondestructive and rapid estimation of leaf nitrogen (N) in agricultural crops, including corn (*Zea mays* L.), rice (*Oryza sativa* L.), and cotton (*Gossypium hirsutum* L.) (Dwyer and others 1994; Peng and others 1993; Turner and Jund 1991; Wood and others 1992a, 1992b). Using this tool to schedule fertilizer applications in a production setting allows managers to increase yields while reducing excessive fertilization that may contaminate surface and ground water (MacKown and Sutton 1998, Shapiro 1999). In spite of the development of this technology in the agricultural community, few studies have explored the value of the SPAD-502 for estimating leaf N of woody crop species. Yet, there is a need for rapid estimation of leaf N in managing short-rotation woody crops; foliar N pools are critical for maximizing tree productivity for fiber, biofuel, and carbon sequestration purposes. Previous work conducted on apple (*Malus domestica* Borkh.) and red maple (*Acer rubrum* L.) illustrates both the potential and the limitations for extending this technology to applications that involve tree species (Campbell and others 1990, Neilsen and others 1995, Sibley and others 1996).

Eastern cottonwood (*Populus deltoides* Bartr. ex Marsh.) is a fast-growing, broadleaf tree species endemic to alluvial sites in the Central and Southeastern United States (Cooper 1990). Because of its rapid growth rate, eastern cottonwood is cultivated extensively in plantations for pulp fiber and timber production throughout regions of North America and Asia (Cao and Conner 1999, Krinard and Johnson 1980). Additionally, there has been a recent surge of interest in using eastern cottonwood plantations for biofuel production, carbon sequestration, soil quality improvement, and catalyzing forest ecosystem restoration on land formerly in row crop production (Stanturf and others 1998, Thornton and others 1998). Compared with other plantation tree species, eastern cottonwood makes high demands on soil nutrients, requiring high levels of available soil N to maximize growth (Blackmon and White 1972, Carter and White 1971). Eastern cottonwood requires leaf N concentrations of at least 2 percent to maximize volume production (Blackmon and White 1972).

When plantations are established on former agricultural fields where soil N has been depleted by previous row cropping, N is commonly the limiting nutrient (Blackmon 1977, Blackmon and White 1972), and fertilization is often needed to reach maximum productivity. Plantation managers needing to assess cottonwood nutrient status lack a rapid field technique for estimating leaf N levels. The objective of this study was to determine if the SPAD-502 chlorophyll meter could be used to estimate leaf N concentration and N content in eastern cottonwood trees established for fiber production on a former agricultural field in the Lower Mississippi River Alluvial Valley.

MATERIALS AND METHODS

The leaf material examined in this study was harvested from a 5-year-old eastern cottonwood plantation located on the Yazoo National Wildlife Refuge, Sharkey County, MS (32°58' N., 90°44'W.). The 24.3-ha cottonwood plantation was established in March 1995 as a component of a large-scale study on forest restoration on former agricultural land (Schweitzer and others 1997). The regeneration and cultural practices used by the Crown Vantage Paper Company

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

in their fiber production operations were followed during plantation establishment; this included a deep application of soluble N prior to planting, but no subsequent fertilizer was applied [for details see Schweitzer and Stanturf (1999) and Schweitzer and others (1997)]. Sharkey clay (very fine, smectitic, thermic, Chromic Epiaquerts) was the predominant soil series on this alluvial site, and the site received an average annual precipitation of 1,318 mm (Scott and Carter 1962).

The eastern cottonwood plantation was established in three 8.1-ha stands (blocks) based on surface soil characteristics that differed according to variation in localized flooding. In early June 2000, eight sample plots were randomly delineated in each of the three stands. Four plots were installed in plantings of the commercially available clone Stoneville-66 (ST-66), while the other four were installed in plantings of the commercially available clone Stoneville-75 (ST-75). These particular clones were chosen for the current study for their widespread commercial deployment and the difference in growth they exhibit during early stand development (Schweitzer and Stanturf 1999). For example, ST-66 averaged 14.7 m tall after five growing seasons, 31 percent taller than the average height of ST-75 (11.2 m) (Fisher and others 2002).

After the sample plots were established, we collected a single leaf sample from 4 adjacent trees in each plot (96 samples: 3 blocks, 2 clones, 4 plots, 4 sample trees). We restricted sampling to mature leaves from the upper one-third of the western aspect of the crown of each sample tree. Furthermore, all leaves were sampled from the same leaf plastocron index (LPI) position (LPI 7 or 8) to ensure nutrient stability (Isebrands and Larson 1973). Sample leaves were harvested between 6 a.m. and 10 a.m. with an extension pole and clipper and were free of insect and disease damage. Dew was blotted from the leaf surface with tissue paper then three readings with a SPAD-502 chlorophyll meter were taken between the midrib and the leaf margin. After chlorophyll meter sampling, sample leaves were placed in polyethylene bags containing moist tissue paper and transported to the laboratory in a refrigerated box.

In the laboratory, the petiole and midrib were dissected from each sample leaf, creating two leaf blade halves. We measured area and green weight of each leaf blade half before randomly selecting one-half for chlorophyll analysis and the other half for N analysis. We conducted chlorophyll analysis according to the methods outlined by Hiscox and Israelstam (1979); results are presented here as total chlorophyll concentration (mass basis) (mg g_{dw}^{-1}) and total chlorophyll content (area basis) (mg dm^{-2}).

Leaf tissue used for N analysis was dried at 70 °C and ground in a ball mill to pass a 100-mesh sieve (Culmo and others 1989). Total N in sample leaf tissue and standards was assessed with a dry combustion technique using a PE 2400 Series II CHNS/O Analyzer (Perkin-Elmer Corporation, Norwalk, CT). Nitrogen analysis results are presented here as total N concentration (mass basis) (percent) and total N content (area basis) (mg dm^{-2}).

We conducted statistical analyses on leaf morphological, chlorophyll, and N variables on sample plot means (mean of four sample trees) according to a randomized block design using SAS software (SAS Institute, Inc., Cary, NC). Regression analyses were used to model relationships between leaf N and chlorophyll and between SPAD values and leaf N. N and chlorophyll values used in the modeling procedures received a natural log transformation to homogenize variance and meet normality assumptions (Myers 1990).

RESULTS AND DISCUSSION

The two eastern cottonwood clones studied in this experiment, ST-66 and ST-75, exhibited differences in leaf morphology and chemistry. ST-75 developed leaf blades with a 25-percent larger area and a 23-percent greater mass than those of ST-66, but leaf mass per area remained similar between the two clones (table 1). N concentrations in leaf tissues were similar for each clone and averaged 1.6 percent across the study site (table 1). Foliar N levels in this study were equivalent to those reported for other eastern cottonwood plantations established on former agricultural fields (Blackmon and White 1972), but were below the optimal 2 percent defined by Blackmon and White (1972) for maximizing productivity. Similar N concentrations and leaf mass per area led to comparable levels of N content per leaf among clones. However, chlorophyll concentration and chlorophyll content of ST-75 leaves were 14 percent and 16 percent greater, respectively, than those of ST-66 (table 1). These findings indicate that ST-75 has a greater proportion of leaf N associated with the chlorophyll fraction than does ST-66. In

Table 1—Leaf morphology, nitrogen and chlorophyll characteristics of two eastern cottonwood clones growing in a 5-year-old plantation, Sharkey County, MS

Variable	Clone ST-66	Clone ST-75	*P*-value
	- - - - - - - mean ± standard error[a] - - - - - - -		
Blade area (dm^2)	0.66 ± 0.03 b	0.83 ± 0.05 a	0.0027
Blade mass (g_{dw})	0.64 ± 0.03 b	0.79 ± 0.06 a	0.0022
Blade mass per area (g_{dw} dm^{-2})	0.97 ± 0.02 a	0.96 ± 0.01 a	0.4734
Total nitrogen concentration (percent)	1.55 ± 0.10 a	1.67 ± 0.05 a	0.0845
Total nitrogen content (mg dm^{-2})	15.0 ± 0.71 a	15.9 ± 0.58 a	0.1209
Total chlorophyll concentration (mg g_{dw}^{-1})	2.69 ± 0.16 b	3.08 ± 0.15 a	0.0125
Total chlorophyll content (mg dm^{-2})	3.65 ± 0.19 b	4.22 ± 0.19 a	0.0025

[a] The sample size for each mean is 12 (3 blocks x 4 plots), and means in a row followed by the same letter do not differ at the 0.05 probability level.

support of the this finding, calculation of N:chlorophyll ratios revealed that ST-66 had 1 mg of chlorophyll for every 4.1 mg of leaf N, while leaves of ST-75 had 1 mg of chlorophyll for every 3.7 mg of leaf N.

Several different models were fit to leaf data to describe relationships between total N (percent and mg dm^{-2}) and total chlorophyll (mg g_{dw}^{-1} and mg dm^{-2}), and between SPAD values and total N (percent and mg dm^{-2}). A curvilinear relationship represented by equation 1 consistently provided the highest coefficient of determination (r^2) values for all relationships.

$$y = \exp\left[a + bx + cx^2\right] \quad (1)$$

Simple linear and curvilinear functions have been used to model these relationships in agronomic crops, as several factors including edaphic conditions, plant phenology, and temporal variation can influence response (Westcott and Wraith 1995; Wood and others 1992a, 1992b). Though the two cottonwood clones exhibited different chlorophyll levels and apparently partitioned differing proportions of N in their chlorophyll fractions, intercept and slope coefficients from models of individual clones did not differ from coefficients of models in which clones were pooled. Thus, results presented here are from the pooled datasets that were used to fit the single curves presented in figures 1A, 1B, 2A, and 2B. Model coefficients for the line in figure 1A are a = -0.399398, b = 1.161110, and c = -0.160611. Model coefficients for the line in figure 1B are a = -0.999735, b = 0.241596, and c = -0.005651. Model coefficients for the line in figure 2A are a = -2.682481, b = 0.196621, and c = -0.002897. Model coefficients for the line in figure 2B are a = 0.596826, b = 0.125604, and c = -0.001680.

Total chlorophyll concentration of eastern cottonwood leaves was strongly associated with leaf N concentration

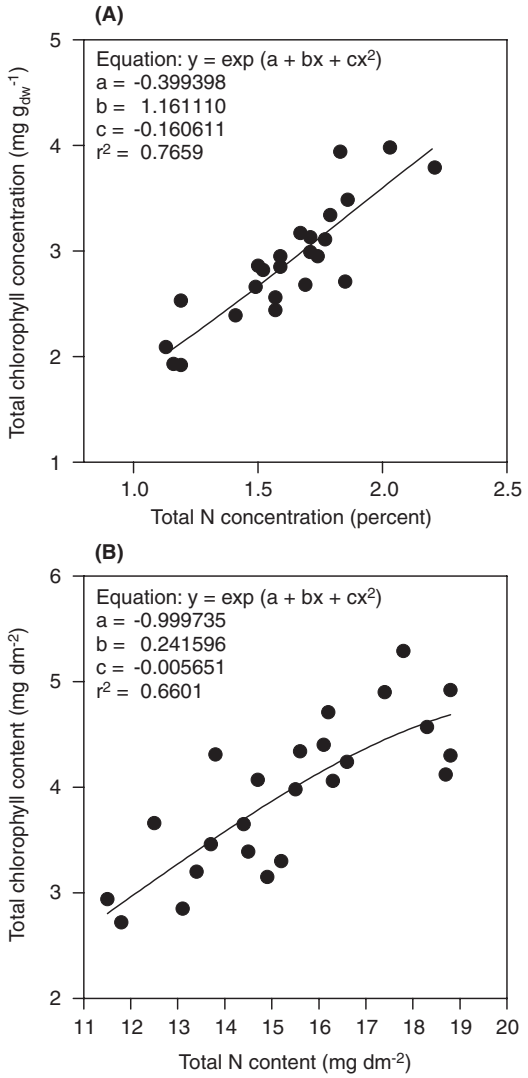

Figure 1—Relationships between total chlorophyll concentration and total nitrogen concentration (A) and between total chlorophyll content and total nitrogen content (B) of eastern cottonwood leaves, Sharkey County, MS.

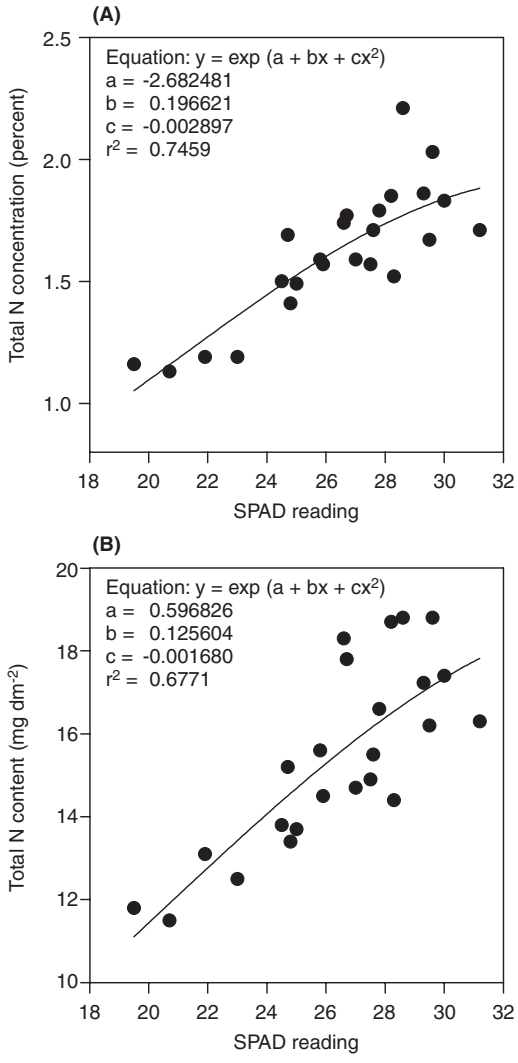

Figure 2—Relationships between total nitrogen concentration and SPAD readings (A) and between total nitrogen content and SPAD readings (B) for eastern cottonwood leaves, Sharkey County, MS.

(P = 0.0001, r^2 = 0.76) (fig. 1A). Within the range of our data, a 0.5-percent increase in N concentration yielded a 0.93-mg g_{dw}^{-1} rise in total chlorophyll concentration. As with N concentration, a significant amount of the variation in leaf chlorophyll content could be attributed to N content (P = 0.0001, r^2 = 0.66) (fig. 1B). However, a greater degree of unexplained variation was associated with this area-based relationship than with the previously described mass-based relationship (figs. 1A and 1B).

Minolta SPAD-502 values showed a strong positive association to total N concentration in eastern cottonwood leaves (P = 0.0001, r^2 = 0.74) (fig. 2A). Fit of prediction curves for eastern cottonwood leaves were in the range reported for several apple cultivars (Neilsen and others 1995). Furthermore, our findings are in contrast to those of Sibley and others (1996), who were unable to demonstrate a significant relationship between SPAD-502 values and foliar N in several red maple cultivars, though others have reported r^2 values as $\geq$ 0.90 for corn and tall fescue (*Festuca arundinacea* Schreb.) (Kantety and others 1996, Wood and others 1992a). Peng and others (1995), who studied rice, suggested that foliar N predictions could be improved if SPAD values were used to estimate N content (area basis) rather than concentration. Findings from this study do not support those of Peng and others (1995); predicting total N content of eastern cottonwood leaves with the SPAD-502 was not as precise as predicting total N concentration (figs. 2A and 2B).

Research conducted by Blackmon and White (1972) and Blackmon (1977) suggested that volume production in eastern cottonwood is greatest when foliar N levels exceed 2 percent. Our observations of leaf N concentrations from the plantation were generally well below this critical amount. The lack of observations > 2 percent prevented us from identifying a SPAD-502 value that would define sufficient foliar N for maximizing eastern cottonwood productivity. However, based on our observations, SPAD-502 values < 32, when measured in the upper canopy, are probably indicative of a N deficiency severe enough to limit eastern cottonwood volume production.

CONCLUSIONS

We used SPAD-502 chlorophyll meter values to accurately determine foliar N concentrations and contents in two clones of 5-year-old eastern cottonwood trees. Though leaves from ST-66 and ST-75 exhibited different amounts of chlorophyll, the coefficients of the regression equations used to predict leaf N were not influenced by clonal variety. Results from this study indicate that SPAD-502 values < 32 are indicative of foliar N concentrations under 2 percent, the threshold N concentration below which volume production of eastern cottonwood is N limited. This research demonstrates the potential utility of the SPAD-502 chlorophyll meter for rapid field determination of foliar N concentration and content in eastern cottonwood trees. This technology could provide short-rotation woody crop managers a quick screening method to identify and quantify N deficiencies in eastern cottonwood stands. Future investigations should be expanded to examine other eastern cottonwood clones on other site types and to standardize sampling protocols for various stages of tree phenology.

ACKNOWLEDGMENTS

This research was conducted while Benoit Moreau was a volunteer intern at the Center for Bottomland Hardwoods Research, Stoneville, MS. We gratefully thank Bart Freeland, Mississippi State University, Extension Service, Stoneville, MS, and Steven Thomson, U.S. Department of Agriculture (USDA), Agricultural Research Service, Stoneville, MS, for providing excellent assistance in the field. Mike Worsham, Charisse Oberle, Dexter Bland, and Paul Hamel, USDA Forest Service, Stoneville, MS, offered invaluable technical support in the field and laboratory. Calvin Meier provided useful comments on an earlier draft of this manuscript.

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SEASONAL SUCROSE METABOLISM IN LONGLEAF PINE TREE STEM CAMBIAL TISSUES

Shi-Jean S. Sung, William J. Otrosina, and Stanley J. Zarnoch[1]

Abstract—This study was a part of a long-term study on factors contributing to the decline of a 40+-year-old longleaf pine stand where prescribed burning has occurred. Burn treatments were implemented between January and March 1997. From April 2002 through February 2003, stem cambial tissues were sampled periodically from healthy longleaf pine trees preselected from each treatment in early April 2002. Sucrose synthase activity increased from April through June but decreased 63 percent from June to July. After several rainstorms in September, the September and October sucrose synthase activity was as high as that of June. The lowest sucrose synthase activity occurred in February. The seasonal pattern of pyrophosphate-dependent phosphofructokinase was similar to that of sucrose synthase. Other measured enzymes in the sucrose metabolic pathway did not show clear seasonal patterns. No treatment effects on these enzyme activities were observed. The seasonal physiological status of longleaf pine trees, as evidenced by their stem cambial sucrose synthase activity, might be useful in determining the optimal time for prescribed burning in longleaf pine stand management.

INTRODUCTION

Longleaf pine (*Pinus palustris* Mill.) is both tolerant of and sensitive to fire, whether prescribed or wild, depending on fire frequency, intensity, and time of occurrence. March burning had more adverse effects on height growth of longleaf pine saplings (approximately 5 to 6 years old) than did burning in May or July (Haywood 2002). Three years after prescribed burning in a 40-year-old longleaf pine stand where temperatures reached approximately 54 to 66 ˚C at duff-soil interface, mortality and number of crown-symptomatic trees had increased after burn treatment (Otrosina and others 2002). Further, increased crown symptom severity was correlated with decreased sucrose synthase activity in longleaf pine stem cambial tissues (Otrosina and others 2002).

Sucrose synthase has been used as a sink strength and physiological status indicator in annual plants (Sung and others 1989b, Xu and others 1989), transplanted loblolly pine (*P. taeda* L.) seedlings (Sung and others 1993b), and loblolly pine trees (Sung and others 1996). The overall objective of this study was to establish the seasonal growth pattern of longleaf pine trees inferred by their cambial tissue sucrose synthase activity. This information will aid ongoing efforts to determine optimal windows for prescribed burning in stands where fire is reintroduced after being long absent.

MATERIALS AND METHODS

The original study was initiated in 1996 at the Savannah River Site (New Ellenton, SC) (Otrosina and others 2002). A 40-year-old planted longleaf pine stand was subjected to four burning treatments in a randomized complete block design. Each 2.0-ha treatment plot was replicated four times with unburned control, cool, medium, and hot burn intensities randomly assigned. Four 0.0079-ha subplots were located in each plot, starting with one at the plot center and three others located 30 m from plot center at 120-degree intervals from due N. Burning took place between January and March 1997. The low- and medium-intensity burns were head fires, whereas the hot burn was a backing fire tending to move more slowly across the landscape. Temperatures at the duff-soil interface registered potentially lethal levels (approximately 54 to 66 ˚C) in the hot-burn plots only. The decomposed organic layer depth in the cool- and medium-burn treatment plots was similar to that of the unburned controls. The hot-burn plots had about one-half the decomposed organic matter of the controls (Otrosina and others 2002).

Periodical sampling of stem cambial tissues for seasonal sucrose metabolic enzyme activities began in mid-April 2002 and continued through February 2003. Due to the summer drought, August sampling was not conducted. Three subplots were randomly selected in each treatment and block. Within each subplot, trees with healthy-appearing crowns were preselected for sampling in early April. A total of 48 trees were sampled each time. After a section of 8- by 15-cm stem bark was peeled; xylem-side cambial tissues were scraped into a weight boat, transferred to plastic bags, and stored immediately in liquid nitrogen. Samples were stored at -80 ˚C until processing. The protein extraction protocol and enzyme assays followed methods described by Sung and others (1993b). Enzymes assayed included sucrose synthase, pyrophosphate-dependent phosphofructokinase, ATP-dependent phosphofructokinase, fructokinase, glucokinase, UDP-glucopyrophosphorylase, phosphoglucomutase, and phosphoglucose isomerase. All enzyme activities were expressed on protein basis. This study was analyzed as a split-plot design with replication by means of four blocks. The whole plot factor was burn treatment (control, cool, medium, hot), while the split-plot factor was the seven sampling months. Thus, blocks were a random factor, while burn treatments and months were fixed factors. The three trees (one from each of three subplots) were considered a random sample of nonsymptomatic trees from each block, burn, and month combination. The random variable for analysis was the mean enzyme

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

activity of the three subplot trees. PROC GLM was used for the analysis of variance, and pairwise comparisons were performed using Tukey's test (SAS Institute 1989). All statistical analyses were performed at the 0.05-significance level.

RESULTS AND DISCUSSION

Mean breast height diameter from all sampled trees was 31.7 cm. No differences in breast height diameter existed among treatments or months of sampling. No burn-treatment effects were observed on any of the eight enzymes assayed over time. To our best knowledge, this is the first report on seasonal sucrose metabolism in longleaf pine trees.

Sucrose synthase activity increased from April to June and decreased significantly (63 percent) in July (fig. 1). The Southeastern United States was in the fifth year of drought in 2002. In fact, August sampling was not conducted due to severe drought conditions. After several rainstorms in early September, both September and October sucrose synthase activity resumed to levels recorded in June (fig. 1). The lowest sucrose synthase activity was found in February 2003 samples, but it was not significantly different from that of July samples. The observed seasonal sucrose synthase pattern in longleaf pine stem was increased activity from early winter through early summer, decreased activity in summer drought, and resumed activity after several rainstorms in early fall. This pattern is similar to that of loblolly pine trees planted at the Savannah River Site (Sung and others 1996). However, loblolly pine did not show significant decreases in sucrose synthase activity from June to August. Loblolly pine seedlings grown in nursery beds for 2 years showed some decreases in stem sucrose synthase activity from June to July in the second year (Sung and others 1993b). It is possible that sucrose synthase activity reduction in longleaf pine stems during summer was caused by either high temperature or drought. Sucrose synthase activity is closely associated with active growth and/or storage in annuals and trees (Otrosina and others 1996; Sung and others 1989a, 1989b, 1993a, 1993b, 1996; Xu and others 1989). In longleaf pine stems, high sucrose synthase activity, thus active growth, began in mid-April and continued through late October (except in July and August). Because we observed low sucrose synthase activity in February, we recommend that burn treatment should be restricted in winter months (December through February) when stem cambial activity is low. Episodic growth patterns of the above- and belowground parts of loblolly pine seedlings and trees have been reported (Sung and others 1993b, 1996). However, during January and February, sucrose synthase activity in both stems and roots of loblolly pine was the lowest. Effects of fire on longleaf pine roots and associated mycorrhizae were also reported in the original burn study and were attributed to delayed mortality in the stand (Otrosina and others 2002). Seasonal sucrose metabolic enzyme patterns in longleaf pine taproots and lateral roots have not been established.

The seasonal pattern of pyrophosphate-dependent phosphofructokinase, but not ATP-dependent phosphofructokinase, was similar to that of sucrose synthase (fig. 1). This was also the case with loblolly pine (Sung and others 1993b, 1996). Like loblolly pine and Jeffrey pine (*P. jeffreyi* Grev. and Balf.) (Otrosina and others 1996), longleaf pine also had similar ATP-dependent phosphofructokinase activity to that of pyrophosphate-dependent phosphofructokinase except in February. Most other tree species, such as sweetgum (*Liquidambar styraciflua* L.) (Sung and Kormanik 2000; Sung and others 1989a, 1993a) and pecan [*Carya illinoinensis* (Wangenh.) C. Koch] (Sung and others 1989a), and many annual plants (Sung and others 1989b, Xu and

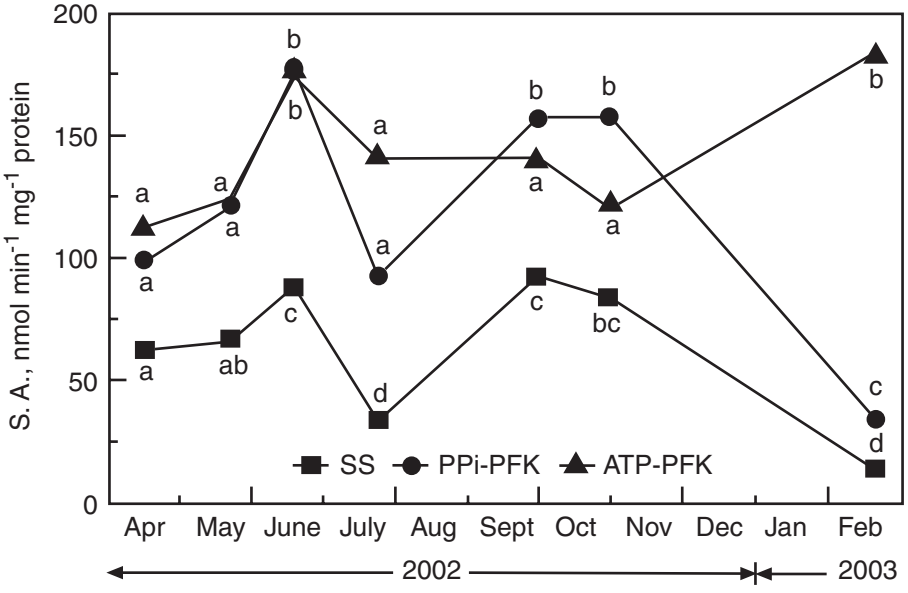

Figure 1—Seasonal patterns of sucrose synthase (SS), pyrophosphate-dependent phosphofructokinase (PPi-PFK), and ATP-dependent phosphofructokinase (ATP-PFK) specific activities (S.A.) in stem cambial tissues of 40+-year-old longleaf pine trees. For each enzyme, different letters indicate significance at the 0.05 level.

others 1989) have twofold to tenfold higher pyrophosphate-dependent phosphofructokinase activity than ATP-dependent phosphofructokinase. Nevertheless, as in other plants (Otrosina and others 1996; Sung and others 1989a, 1993b, 1996; Xu and others 1989), ATP-dependent phosphofructokinase in longleaf pine functioned as a maintenance enzyme that did not change its activity with seasons or environments. This was evident with the high level of ATP-dependent phosphofructokinase activity occurring in February when pyrophosphate-dependent phosphofructokinase was only 20 percent of the former (fig. 1).

Glucokinase activity was most active in spring and least active in summer and winter (fig. 2). Low levels of fructokinase also was observed in longleaf pine, loblolly pine (Sung and others 1993b, 1996), and Jeffrey pine (Otrosina and others 1996). Compared to activities of sucrose synthase and pyrophosphate-dependent phosphofructokinase (fig. 1), activities of UDP-glucopyrophosphorylase, phosphoglucomutase, and phosphoglucose isomerase were elevated (fig. 3). Monthly differences in these enzyme activities were not biologically significant, although some were statistically significant. These enzyme levels were

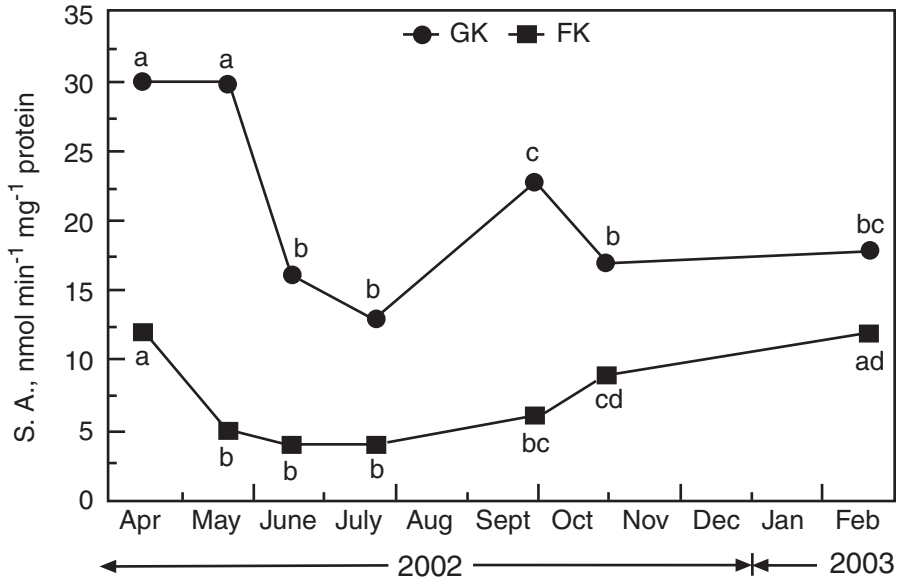

Figure 2—Seasonal patterns of fructokinase (FK) and glucokinase (GK) specific activities (S.A.) in stem cambial tissues of 40+-year-old longleaf pine trees. For each enzyme, different letters indicate significance at the 0.05 level.

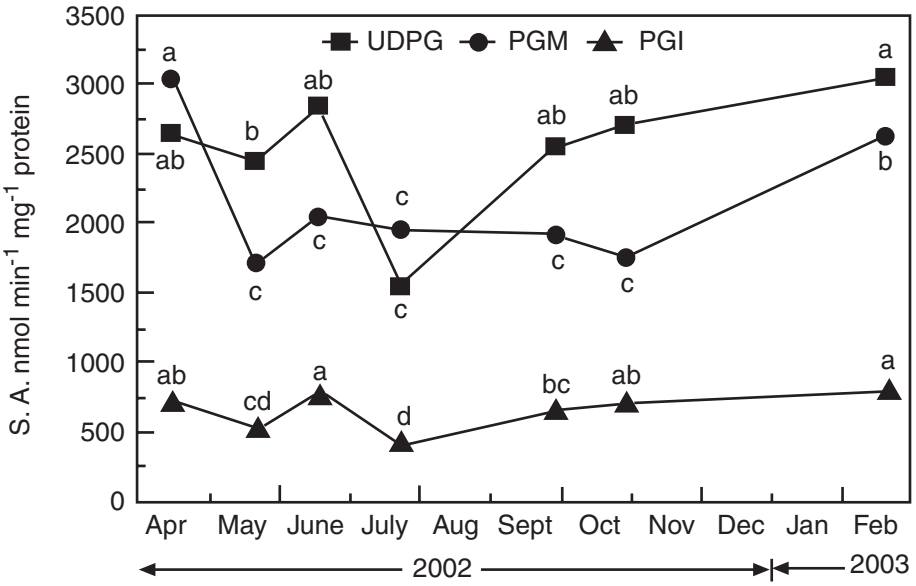

Figure 3—Seasonal patterns of UDP-glucopyrophosphorylase (UDPG), phosphoglucomutase (PGM), and phosphoglucose isomerase (PGI) specific activities (S.A.) in stem cambial tissues of 40+-year-old longleaf pine trees. For each enzyme, different letters indicate significance at the 0.05 level.

similar to values reported for other trees (Sung and others 1989a) and annual plants (Xu and others 1989).

CONCLUSIONS

Seasonal sucrose metabolism in longleaf pine tree stem cambial tissues resembled that of loblolly pine trees (Sung and others 1996). After low activity in February, sucrose synthase activity increased from April until June. In summer when rainfall was scarce, significant decreases in stem cambial sucrose synthase activity indicated that stem diameter growth may be affected. Sucrose synthase activity resumed in fall. The seasonal activity of pyrophosphate-dependent phosphofructokinase followed that of sucrose synthase. Activities of other enzymes in the sucrose meatabolic pathway did not have clear seasonal patterns, or their seasonal differences were biologically insignificant. Future studies involving annual sucrose metabolism and growth in longleaf pine roots will provide important information in determining the optimal window for reintroduction of fire into longleaf pine stands.

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Bottomland Hardwoods — Natural Regeneration

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A COMPARISON OF OAK REGENERATION CONDITIONS FOLLOWING MIDSTORY INJECTION AND PARTIAL OVERSTORY REMOVAL IN A TOMBIGBEE RIVER TERRACE

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Abstract—Bottomland hardwood stands comprised of a large oak component can be regenerated through natural oak regeneration. To maximize oak regeneration potential, the stand manager must practice silvicultural techniques that allow for necessary sunlight penetration to reach the forest floor. Control of stems occupying the midstory/understory and partial overstory removal are steps that may be required to ensure adequate stocking levels of natural regeneration. While the need for midstory/understory control has been documented, questions often arise regarding the level of intensity of overstory removal. Natural regeneration responses of oak species were observed 1 year after a midstory/understory injection treatment and partial overstory removal. Treatments were conducted on a bottomland hardwood stand near Bellamy, AL. The study area consisted of four 12-acre blocks with three 4-acre treatment units located in each block. The study design was a randomized complete block. Injection treatments using imazapyr were applied during late fall of 2001. There was no negative impact from the injection observed on non-target stems, and seedling establishment generally increased. Partial overstory removal treatments were completed with operational harvests, leaving residual stand basal areas of 30, 50, and 70 square feet. Seedling survival was observed from data collected from 108 0.01-acre sample plots. Results indicate that seedling survival was impacted by harvest. Damage occurring from logging operations was also evaluated on all residual trees.

INTRODUCTION

To establish natural regeneration in a hardwood stand, land managers need an understanding of silvicultural procedures involved. Silvicultural applications such as midstory/understory control and partial harvests may be required to ensure adequate stocking of oak regeneration to promote the future stand. Control of undesirable species using imazapyr causes mortality to injected stems, enhances regeneration, and does not damage crop stems (Ezell and others 1999). The level of the partial harvest intensity may impact the amount of advance reproduction present following harvesting activity. The intensity of partial harvest affects the amount of sunlight penetration that reaches the forest floor. Gardiner and Hodges (1998) found that oak seedling growth was maximized when sunlight availability was between 27-53 percent. Low understory light levels present in bottomland stands may be the most limiting factor on the establishment and growth of oaks (Hodges and Gardiner 1993). Thus, land managers need to understand how these practices can influence oak regeneration.

The amount of harvesting damage occurring to residual stems following harvesting activity is also an important consideration. Potential losses due to reduction of residual stems' log grade can be assessed if an estimation of damage can be depicted. The intensity of partial harvesting might also impact the amount of initial oak regeneration following harvesting. The objectives for this study are (1) to evaluate the effect of midstory/understory control on initial oak regeneration, (2) determine the impact of harvesting activity on initial oak regeneration, and (3) to evaluate damage resulting from varying harvest intensities.

MATERIALS AND METHODS

Study Site Description

The study site is located near Bellamy, AL on property owned by Delaney Development, Inc. and managed by Springdale Land Management. The hardwood stand is situated on a terrace micro-geographical position along the Tombigbee River. Stand composition is a mixed oak bottomland forest with a well developed midstory. Species occupying the overstory include water oak (*Quercus nigra* L.), swamp chestnut oak (*Q. michauxii* Nutt.), white oak (*Q. alba* L.), cherrybark oak (*Q. pagoda* Raf.), sweetgum (*Liquidambar styraciflua* L.), and various hickory species (*Carya* spp.). The understory and midstory tree species primarily consist of American hornbeam (*Carpinus caroliniana* Walt.), eastern hophornbeam (*Ostrya virginiana* Mill.), American beech (*Fagus grandifolia* Ehrh.), and winged elm (*Ulmus alata* Michx.), with scattered oak species.

STUDY DESIGN

The study was arranged as a randomized complete block design. The research site consisted of four rectangular blocks that were 12.06 acres in size. Three of these blocks were utilized as "treatment areas" while retaining one block as control. A midstory/understory control treatment using imazapyr was applied during the dormant season of 2001-2002. All four blocks were divided into three treatment units encompassing an area of 4.02 acres each. The experimental unit consisted of treatment unit conditions prior to and following partial harvests which maintained residual basal areas of 70, 50, and 30 square feet. These partial harvest intensities were replicated once in treatment units for each of the three "treatment areas."

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

The partial harvest activity occurred during September of 2002. These harvests were conducted by Kynard Logging contracted by Springdale Land Management. Large diameter trees were felled with chainsaws then topped, delimbed, and cut to length prior to being skidded. Stems with large canopies used for pulpwood were topped and limbed in place. Smaller sized stems used for pulpwood were topped and delimbed at the loading decks. Wheeled, articulated skidders were used to move raw wood materials to loading decks located at the east boundaries of the treatment blocks. Weather conditions during the time of harvest were dry.

DATA COLLECTION AND ANALYSIS

Pre-harvest overstory basal area was inventoried on the site. All overstory stems were measured for diameter at breast height (d.b.h.). Basal area for individual stems was determined using the formula:

basal area = d.b.h.^{2} * 0.005454.

These data allowed for estimations of basal area for all species occupying treatment units and served as a basis for determining trees to be removed to achieve desired basal areas following partial harvests.

Oak regeneration sampling was conducted on 108 0.01-acre sample plots. Oak seedlings within these plots were tallied by species and height classes. Height classes included seedlings less than 1 foot in height and 1-3 feet in height. Sampling was conducted prior to harvesting activity during April 2002 and following harvesting activity in November 2002. Harvesting damage occurring on residual stems was also quantified. Damage was categorized by height classes and damage area or size classes. Height classes occurred at three-foot intervals starting at ground level. Size classes had a range of 40 square inches (e.g., 0-40, 41-80, etc.).

RESULTS AND DISCUSSION

Regeneration sampling data indicated that the majority of oak seedlings were in the height classes of < 1 foot and 1-3 feet for both pre- and post-harvest measurements. Pre-harvest measurements were analyzed to determine the impact of applying midstory/understory control. These data compared the three treated blocks against the control block. Results derived from sampling data showed that oak regeneration generally increased following the midstory/understory control treatment. Results for block 1 indicate that oak regeneration decreased by 5.57 percent compared to control. Blocks 2 and 3 increased by 71.08 percent and 79.44 percent, respectively, compared to control. The increased amount of oak regeneration can be attributed to greater amounts of sunlight penetration reaching the forest floor. The increased abundance of sunlight results from the control of live stems occupying the midstory/understory level of the stand.

The intensity of harvesting activity also impacted the amount of oak regeneration following partial harvest. Evaluations to determine the impact harvesting intensity had on oak regeneration were derived by comparing pre-harvest measurements to post-harvest measurements for the nine treatment units on blocks 1 to 3. Three treatment units suffered the greatest decreases in oak regeneration due to excessive skidding activity. These units were located adjacent to logging decks. These blocks were excluded in the analysis to determine initial oak regeneration responses to partial harvesting intensity. The two treatment units that had residual basal areas of 50 square feet showed the largest increases in initial oak regeneration. This intensity of partial harvest promoted greater regeneration due to the combination of harvest activity and light penetration. Individual treatment unit percentages of increase/decrease are depicted in table 1.

Another observation made from regeneration data was that water and willow oak seedlings increased in abundance more than other oak species. This response was observed on the four treatment units that had increased percentages of initial oak regeneration. These two species had a bumper acorn crop during the fall of 2001. Partial harvest activity occurred following this year, which may have promoted the increase of seedlings from these two species. Findings from this study tend to indicate that conducting harvesting activity following good seed crop years can increase oak regeneration success.

Analysis to determine the impact of harvesting intensity on damage occurring to residual stems showed similar trends between treatments. The majority of damage occurred below 3 feet on the butt logs of the residual trees. Greater than half of the residual trees were undamaged on all treatment units. This indicated that regardless of the partial harvest intensity applied, the majority of residual stems will be undamaged following harvest activity. Treatment units with residual basal areas of 70 square feet had the lowest percentage of damaged residual stems among the three treatments. The percentages of damage occurrence for the three residual basal areas are illustrated in table 2.

Table 1—Harvesting impacts on regeneration

	Treatment—residual basal area	Oak seedling change	Adjacent to loading deck
	square feet	*percent*	
Block one	50	-59.50	Yes
	30	-3.05	No
	70	-13.45	No
Block two	30	-53.10	Yes
	70	30.22	No
	50	101.00	No
Block three	70	-32.07	Yes
	50	115.93	No
	30	8.15	No

Table 2—Percentage of damage occurrence on residual stems by height class

Height classes	Basal area (*square feet*)		
	30	50	70
feet	- - - - - - - - *percent* - - - - - - - -		
0–3	87.91	77.95	86.51
3–6	9.89	18.90	11.11
6–9	2.20	3.15	2.38

The size of damaged areas on residual stems also showed a similar pattern between treatments. Generally, smaller "damage zones" occurred more frequently than larger "damage zones." The majority of stems had damage areas of less than 80 square inches in size. This can be attributed to proper logging techniques employed by the loggers. The percentages of damage area size compared to residual basal area are presented in table 3.

Table 3—Percentage of residual stems exhibiting various amounts of harvest damage by treatments

		square inches		
Basal area	No damage	< 80	81-160	> 161
square feet	- - - - - - - - - - - - - *percent* - - - - - - - - - - - - -			
30	50.57	36.78	9.77	2.87
50	54.89	32.34	5.96	6.81
70	74.84	19.31	2.82	3.04

SUMMARY

The two types of silvicultural treatments conducted during this experiment tended to show positive effects on initial oak regeneration. Midstory/understory control promoted regeneration of desirable species while removing less desirable stems and increasing sunlight penetration to the forest floor. Oak regeneration reached the highest levels on the treatment units that received partial harvests leaving a residual basal area of 50 square feet. The amount and type of initial regeneration was dependent on species present in the stand. This was clearly evident in the case of water and willow oak. Results showed that harvesting in conjunction with a good mast crop tended to enhance initial regeneration.

This study also found that there was a strong negative association between skidder activity and oak regeneration. Areas closer to loading decks had a larger reduction in the amount of visible initial regeneration due to increased usage by large machinery. These areas of high impact may, however, regenerate in the future. The majority of damage resulting from harvesting activity will generally tend to be located between the ground and the first 3 feet of butt logs on residual trees. Smaller damaged areas will be more prevalent than larger areas on these logs as well. To reduce the amount of damage occurring to regeneration and residual stems, land managers may opt to either consolidate or spread skid trails out over harvest areas while also ensuring proper logging techniques are applied to hardwood stands.

ACKNOWLEDGMENTS

This project was supported by Delaney Development, Inc. Assistance was also given by Springdale Land Management for contracting of the logging company as well as aiding in the research process.

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REGENERATION DEVELOPMENT 3 YEARS AFTER THINNING AND FERTILIZATION IN AN EAST TEXAS BOTTOMLAND HARDWOOD STAND (TO MANAGE OR TO REGENERATE: CAN WE DO BOTH?)

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Abstract—Silviculture textbooks state that intermediate treatments, such as thinning, are prescribed to regulate the growing space for the benefit of existing trees and not to create enough growing space to initiate new trees of desirable species. If new, desirable regeneration develops, then it is considered a by-product of the intermediate treatment and is not to be managed, else the operation is a reproduction. In bottomland hardwood management where oaks (*Quercus* spp.) are the primary species being managed, new oak reproduction often initiates following a thinning operation, especially if the operation coincides with an exceptionally good acorn crop. Given past difficulties in regenerating bottomland oaks, an opportunity exists to promote the development of this reproduction during future thinning operations where growth and development of desired overstory crop trees is still the primary objective. Results following 3 years of crown thinning and low thinning, along with a fertilization treatment, showed few differences in the density and development of oak reproduction compared to unthinned plots, but an oak regeneration pool is developing. We believe the lack of differences reflect the young nature of the stand, i.e., it is just entering acorn production age. Future thinnings should enhance the establishment and development of oak reproduction despite the concurrent development of future midstory canopy species such as American hornbeam (*Carpinus caroliniana* Walt.) and deciduous holly (*Ilex decidua* Walt.).

INTRODUCTION

The first decision a forest resource manager faces when initiating a management program for an existing bottomland hardwood stand, after determining the management objectives, is whether to continue managing the existing stand or begin steps to secure regeneration. A decision model, HARDWOOD, was recently developed to help forest resource managers with this initial decision (Belli and others 1993). The model takes into account aspects of each tree in designated inventory plots including tree class, species, crown class, butt log grade, vigor, and merchantable length (Manuel and others 1993). If the decision is to manage the existing stand, then the forester has options regarding intermediate treatments, such as release or thinning, depending on management objectives and current stand structure (Meadows 1996). If the decision is to regenerate the existing stand, then the forester must determine if adequate natural regeneration exists (Belli and others 1999, Hart and others 1995, Johnson 1980), determine the steps needed to secure adequate advance regeneration if inadequate regeneration exists (Clatterbuck and Meadows 1993), or utilize artificial regeneration (Gardiner and others 2002).

This initial decision, to manage or to regenerate the existing hardwood stand, reflects traditional silviculture (Daniel and others 1979, Nyland 2002, Smith and others 1997). When managing an existing stand, reproduction that initiates and develops following an intermediate treatment is simply an artifact of the disturbance and is ignored, else the operation is considered a regeneration cutting instead of an intermediate treatment. Continued development of this reproduction, especially if shade-intolerant to moderately tolerant species, is considered an inefficient use of growing space for overstory tree growth and development, i.e., a poor marking and/or logging operation. The dichotomy, to manage or to regenerate, works well with species that are relatively easy to regenerate such as loblolly pine (*Pinus taeda* L.). For species that are more difficult to regenerate, such as the oaks (*Quercus* spp.) (Loftis and McGee 1993), a gray area may exist in this dichotomy where intermediate treatments that focus on residual tree growth and development may also be used to initiate and/or promote the development of desirable advance reproduction. The objective of the research project described in this paper is to follow the establishment and development of reproduction following thinning and fertilization in a bottomland hardwood stand. Three-year post-treatment results are reported.

MATERIALS AND METHODS

Study Site

The study was conducted on the Shawnee Creek floodplain, a minor bottom (Hodges 1997), in Angelina County, east-central Texas. The climate is characterized as long, hot summers and cool, fairly short winters (Dolezel 1988). The average annual temperature is 67 °F with a monthly average high ranging from 48 °F in January to 83 °F in July. Precipitation occurs throughout the year, averaging 41 inches per year with a monthly average of 2.5 inches in August to 4.3 inches in May. Prolonged droughts are rare (Dolezel 1988). Flooding occurs annually for brief periods. Soils are of the Pophers series (fine-silty, siliceous, acid, thermic Aeric Fluvaquents). Site index, base age 50 years, was estimated to be 90 to 95 for cherrybark oak (*Q. pagoda* Raf.), water oak (*Q. nigra* L.), and willow oak (*Q. phellos* L.) using the Baker/Broadfoot soil-site evaluation method

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

(Baker and Broadfoot 1979). The study site was originally planted to loblolly pine around 1970 following mechanical site preparation (shearing). Herbicides were not used. Pine survival was poor due to flooding and the site reverted to an even-aged bottomland oak stand (see table 1 for initial stand characteristics). Stand age at the time of study installation was about 30 years.

Treatments and Study Design

Three levels of thinning and two levels of fertilization were applied in this study. Thinning consisted of no thinning (control), low thinning, and crown thinning. Low thinning consisted of removing all trees from the intermediate and suppressed crown classes [see Meadows and others (2001) for a description of hardwood crown classes]. No trees in the dominant and codominant crown classes were removed. Crown thinning consisted of removing trees in the codominant and dominant crown classes. No trees in the intermediate and suppressed crown classes were removed. A tree class system was developed [see Meadows (1996) for a description of tree classes] to select leave trees (crop trees) in each thinning treatment. In short, crop trees were of desired species (red oaks when possible), possessed healthy crowns, either contained or had the potential to develop a grade 1 butt log, had few to no epicormic branches on the butt log, and were disease free. Crop trees were released on at least two of four possible sides in the upper canopy in the crown thinning treatment. Marking was conducted in February 1999 with thinning conducted the following month. Due to wet soil conditions, trees were chainsaw felled and left in place.

Fertilization consisted of no fertilization (control) and 200 pounds of nitrogen per 50 pounds of phosphorus per acre applied as di-ammonium phosphate. The fertilization treatment was based on standard fertilization practices in intensive loblolly pine silviculture in the Atlantic Coastal Plain region (Jokela and Stearns-Smith 1993, North Carolina State Forest Nutrition Cooperative 2000). The fertilizer was applied to designated plots in June 1999, later than planned due to early spring flooding on the study site. Application was accomplished using hand-held spreaders. Treatments were randomly assigned to one-half acre rectangular plots with a designated one-quarter acre interior measurement plot. Six plots, 1 for each thinning and fertilizer combination, were utilized in each of 4 blocks in a randomized complete block design (24 total plots).

Measurements

Prior to treatment, all trees ≥ 3.6 inches d.b.h. (4-inch diameter class) were identified by species and had their d.b.h. measured (diameter at breast height, 4.5 feet above the ground) and crown class assessed. Two 0.01-acre circular regeneration plots were systematically installed in each plot. All stems in the regeneration plots were tallied by species into the following height classes: (1) < 1 foot tall, (2) 1 foot to 3 feet tall, (3) > 3 feet tall but less than 1 inch d.b.h. (using d.b.h. classes such that the one-inch class was 0.6 to 1.5 inches d.b.h.), and (4) 1 inch to 3 inches d.b.h. Additional measurements for all oak stems ≥ 1 foot tall included actual height [in centimeters (cms)]. Distance and azimuth from plot center were recorded for these seedlings for future measurements. All measurements were conducted during the early dormant season for each of the 3 years after treatment.

Analyses

Regeneration subplots were combined in each plot and scaled to per acre values. Analysis-of-variance was used to determine if differences in seedling density and height existed. Density values were transformed using the log transformation before analyses (untransformed data are shown in all tables and figures). Seedling heights were analyzed using initial seedling height as a co-variate. Duncan's Multiple Range Test was used to detect differences between treatments ($p \leq 0.10$). Metric height measurements were converted to English units in all tables.

RESULTS AND DISCUSSION

Regeneration Density

Few differences existed in total regeneration density and oak regeneration density between treatments, even when analyzed by regeneration size class. High variability existed between regeneration plots within and between treatments. Therefore, the results and discussion below pertain to combined density across all treatments.

Pre-treatment regeneration consisted of 35 tree species with an average density of 3,297 stems per acre (spa) (table 2). Total regeneration density decreased 43 percent following the first year after treatment before increasing to about 2,100 spa the following two years. Greatest changes in density occurred in the < 1 foot tall size class (table 2). The number of seedlings < 1 foot tall decreased 54 percent 1 year after thinning and fertilization. Seedlings < 1 foot tall

Table 1—Pre-treatment trees per acre (d.b.h. ≥ 3.6 inches), d.b.h. (quadratic mean), basal area, andstocking (using Goelz 1995) for all trees and crop trees in an east Texas bottomland hardwood stand

Trees	Tree per acre	d.b.h.	Basal area per acre	Stocking
		inches	*square feet*	*percent*
All trees	311(216-432)	8.5(7.4-9.8)	123(100-150)	115(92-141)
Crop trees	45(16-84)	11.6(9.6-14.2)	33(18-48)	28(15-40)

Values in parentheses represent the maximum and minimum mean plot values.

Table 2—Regeneration density per acre for all tree species in an east Texas bottomland hardwood stand 1 year prior and 3 years following thinning and fertilization[a]

Size class	Pre-treatment 1999	1999	2000	2001
< 1 foot tall	2,800 (± 653)	1,300 (± 432)	977 (± 266)	1,225 (± 535)
1 foot - 3 feet tall	296 (± 109)	434 (± 194)	848 (± 390)	538 (± 209)
> 3 feet tall - < 1 inch d.b.h.	51 (± 37)	42 (± 30)	144 (± 65)	163 (± 112)
1 inch - 3 inches d.b.h.	150 (± 103)	88 (± 46)	219 (± 95)	173 (± 57)
Total	3,297 (± 742)	1,864 (± 618)	2,188 (± 585)	2,099 (± 678)

Values in parentheses represent 1 standard error.
[a] All thinning and fertilization treatments combined.

are relatively new seedlings, usually 1 to 2 years old (personal observation). Population fluctuations in seedlings < 1 foot tall are expected since they usually arise from bumper seed crops. Their relatively small root systems combined with low leaf areas growing in partially shaded to heavy shaded environments, especially for shade intolerant to moderately shade intolerant species, predisposes them to rapid mortality. Further, these seedlings are most likely to perish during flooding episodes, especially during the growing season.

Another reason for the decrease in the number of seedlings < 1 foot tall was continued growth into the larger size classes (table 2), especially for those seedlings that could acquire and utilize additional resources. Seedling density increased 32 percent and 65 percent from the < 1 foot tall size class to the 1 foot to 3 feet tall size class one and two growing seasons after treatment, respectively. Increases were also noted in the > 3 feet tall but < 1 inch d.b.h. and 1 inch to 3 inch d.b.h. size classes, especially after the 2000 growing season. The decrease in these latter two size classes following one growing season after treatment may be due to damage that occurred to these larger seedlings and saplings during the thinning operations. The decrease in three of the four size classes following the 2001 growing season (table 2) may also be due to growth into larger size classes. Initial seedling density for the > 3 feet tall but < 1 inch d.b.h. size class in the crown thinning-no fertilization treatment was 13 spa. This density increased to 88, 288, and 425 spa following the 1999, 2000, and 2001 growing seasons, respectively. Decreases in density among the other treatments may be due to canopy closure from the thinning and fertilization treatments.

A majority of the initial seedling density was composed of oak species (75 percent), including white (*Q. alba* L.), overcup (*Q. lyrata* Walt.), swamp chestnut (*Q. michauxii* Nutt.), water, cherrybark, and willow oaks. Throughout the 3 year study period, greatest density within the oak regeneration size classes was seedlings < 1 foot tall (table 3). Population fluctuations were again noted in this size class. Increases in the 1 foot to 3 feet tall size class are the result of growth of oak seedlings from the < 1 foot tall size class with a nearly 100 percent increase in density from 1999 to 2001. Unfortunately, practically no increase has occurred in the 2 largest size classes, > 3 feet tall to < 1 inch d.b.h. and 1 inch to 3 inches d.b.h. Lack of growth into these size classes reflects the slow initial growth of oak seedlings following a disturbance that increases light levels reaching the seedlings (Deen and others 1993, Janzen and Hodges 1987, Lockhart and others 2000).

Of particular note is the density of other species in the larger size classes (> 3 feet tall but < 1 inch d.b.h. and 1 to 3 inches d.b.h.). American hornbeam (*Carpinus caroliniana* Walt.) and deciduous holly (*Ilex decidua* Walt.), two species

Table 3—Regeneration density per acre for oak species in an east Texas bottomland hardwood stand 1 year prior and 3 years following thinning and fertilization[a]

Size class	Pre-treatment 1999	1999	2000	2001
< 1 foot tall	2,302 (± 672)	1,098 (± 342)	823 (± 272)	1,106 (± 506)
1 foot - 3 feet tall	169 (± 79)	261 (± 137)	398 (± 210)	329 (± 155)
> 3 feet tall - < 1 inch d.b.h.	2 (± 2)	6 (± 6)	13 (± 11)	9 (± 9)
1 inch - 3 inches d.b.h.	6 (± 6)	2 (± 2)	11 (± 11)	2 (± 2)
Total	2,480 (± 743)	1,367 (± 460)	1,244 (± 437)	1,446 (± 582)

Values in parentheses represent 1 standard error.
[a] All thinning and fertilization treatments combined.

noted for their shade tolerance and midstory canopy development, along with hickories (*Carya* spp.), are prominent members of these larger reproduction size classes (table 4). American hornbeam and deciduous holly comprised 42 percent of the seedlings and saplings in the 2 largest size classes after the 2001 growing season while oaks represented 3 percent (tables 2, 3, and 4). Hickory species *C. cordiformis* (Wang.) K. Koch, *C. glabra* (Mill.) Sweet, *C. ovata* (Mill.) K. Koch represented 12 percent of these seedlings and saplings. The hickory species, when combined with American hornbeam and deciduous holly, comprised 54 percent of the total regeneration pool in the > 3 feet tall but < 1 inch d.b.h. and 1 to 3 inches d.b.h. size classes. American hornbeam, deciduous holly, and possibly the hickories, are probably of the same age as the overstory, having initiated in the early 1970s following site preparation and loblolly pine planting. Their presence represents the initial regeneration floristics that follow a major forest disturbance (Egler 1954, Oliver 1981). Their presence in the larger regeneration size classes in this 30-year-old stand also represents normal stand development in minor creek bottoms in the west Gulf Coastal Plain (Bowling and Kellison 1983, Johnson and Krinard 1988). Continued development of these species will result in a moderately dense midstory canopy. Without future silvicultural intervention, this midstory canopy will be detrimental to continued oak seedling establishment and development (Janzen and Hodges 1987, Lockhart and others 2000).

Oak Seedling Development

Eighty-two oak seedlings > 1 foot tall were initially flagged for future measurement (table 5). These seedlings were distributed across the treatments with a maximum of 18 in the low thin-fertilization treatment and a minimum of 8 in the crown thin-no fertilization treatment. Oak seedling survival was relatively poor throughout the 3 year study period, ranging from 50 percent in the low thin-no fertilization treatment to 5 percent in the crown thin-fertilization treatment. While no statistical differences were found between treatments an interesting pattern may be developing that at least allows for making hypotheses for future testing. Survival in the no thin treatment has dropped considerably over the 3 year period, averaging 15 percent by the end of the 2001 growing season. We hypothesize that these seedlings simply do not receive enough sunlight for survival, much less growth. Lockhart and others (2000) noted low survival rates of cherrybark oak seedlings in mature bottomland hardwood stands with a prominent

Table 4—Regeneration density per acre for selected species and selected size classes in an east Texas bottomland hardwood stand 1 year prior and 3 years following thinning and fertilization[a]

Size class	Pre-treatment 1999	1999	2000	2001
American hornbeam and deciduous holly				
> 3 feet tall - < 1 inch d.b.h.	36 (± 31)	7 (± 7)	65 (± 36)	63 (± 53)
1 inch - 3 inches d.b.h.	65 (± 58)	23 (± 18)	102 (± 80)	79 (± 40)
Hickory species				
> 3 feet tall - < 1 inch d.b.h.	4 (± 2)	7 (± 7)	7 (± 4)	9 (± 7)
1 inch - 3 inches d.b.h.	23 (± 13)	27 (± 17)	32 (± 14)	30 (± 20)

Values in parentheses represent 1 standard error.

[a] All thinning and fertilization treatments combined.

Table 5—Survival (percent) of oak reproduction (initial seedling height ≥ 1 foot) by treatment in an east Texas bottomland hardwood stand 3 years following thinning and fertilization. Values in parentheses represent 1 standard error

Thinning treatment	Fertilization treatment	n[a]	1999	2000	2001
No	No	14	88 (± 9)	32 (± 11)	12 (± 9)
	Yes	13	54 (± 12)	45 (± 14)	18 (± 8)
Low	No	16	71 (± 2)	58 (± 5)	50 (± 0)
	Yes	18	67 (± 14)	53 (± 7)	36 (± 11)
Crown	No	8	56 (± 17)	56 (± 17)	38 (± 19)
	Yes	13	63 (± 19)	38 (± 17)	5 (± 4)
p-value			.5493	.7916	.4012
Survival across treatments			67 (± 12)	47 (± 12)	27 (± 9)

[a] n represents the number of oak seedlings ≥ 1 foot across all replicates within a thinning and fertilization treatment combination.

midstory canopy. We also hypothesize the low oak seedling survival rate in the crown thin-fertilization treatment may reflect intense herbaceous competition. While not directly measured, it was noted that crown thin-fertilization treatments resulted in dense herbaceous, and particularly grass, cover.

Height development of these oak seedlings was generally poor (table 6). Initial seedling height was 14 inches and increased to 21 inches by the end of the 2001 growing season. No differences were found between treatments but, as with oak seedling survival, an interesting pattern may be occurring. Seedlings in the thinning treatments appear to be responding to the increased light levels compared to seedlings in the unthinned treatments. The lack of a statistical difference probably reflects the low number of sample seedlings with an associated high variability between treatments, especially for the low thin-fertilization treatment (table 6). Bottomland red oaks have been shown to respond to increases in light levels following midstory competition control (Deen and others 1993, Janzen and Hodges 1987, Lockhart and others 2000).

Height development of oak seedlings > 1 foot tall, including those that grew to this minimum height for measurement during the past 3 years, indicates that oak seedlings are responding to the treatments (table 7). Oak seedlings in the low thinned-fertilized treatment were taller than seedlings in the unthinned treatments after one growing season. This statistical difference disappeared the following 2 years, in part to an increase in the number of oak seedlings growing into the ≥ 1 foot tall size class. Increases in height development over time appear to be occurring but high variability prevents these differences from yet being statistically significant. These trends in height development, for both the original pool of oak seedlings ≥ 1 foot tall and the combined original seedlings and new seedlings that have grown into the ≥ 1 foot tall size class indicate that an oak seedling bank is developing in this mid-rotation aged bottomland oak stand.

Table 6—Height (inches) development of oak reproduction initially ≥ 1 foot tall by treatment in an east Texas bottomland hardwood stand 1 year prior and 3 years following thinning and fertilization

Thinning treatment	Fertilization treatment	Pre-treatment 1999	1999	2000	2001
No	No	13 (± <1)	12 (± 4)	14 (± 6)	14[a]
	Yes	15 (± 1)	14 (± 1)	13 (± <1)	17 (± 5)
Low	No	13 (± <1)	10 (± 2)	12 (± <1)	15 (± 1)
	Yes	16 (± 1)	21 (± 4)	28 (± 13)	31 (± 17)
Crown	No	14 (± <1)	17 (± 1)	21 (± 4)	33 (± 1)
	Yes	14 (± 1)	13 (± 2)	16 (± 5)	5a
p-value		.2566	.1387	.3822	.7679
Height across treatments		14 (± 1)	15 (± 2)	17 (± 5)	21 (± 4)

Values in parentheses represent 1 standard error.

[a] Only one treatment replication contained oak seedlings so no standard error of the mean could be calculated.

Table 7—Height (inches) development of oak reproduction initially ≥ 1 foot tall and those seedlings that grew into the ≥ 1 foot height class by treatment in an east Texas bottomland hardwood stand 3 years following thinning and fertilization

Thinning treatment	Fertilization treatment	1999	2000	2001
No	No	13 (± 1) B[a]	13 (± 2)	15 (± 1)
	Yes	14 (± 1) B	13 (± 1)	15 (± 2)
Low	No	12 (± 1) B	12 (± 1)	15 (± < 1)
	Yes	20 (± 3) A	18 (± 2)	20 (± 4)
Crown	No	17 (± 1) AB	19 (± 1)	21 (± 2)
	Yes	13 (± 2) B	17 (± 2)	19 (± 2)
p-value		.0165	.1039	.1530
Height across treatments		15 (± 4)	15 (± 4)	17 (± 5)

Pre-treatment 1999 values are the same as Table 6.

Values in parentheses represent 1 standard error.

Means followed by a different letter within a column are significantly different at p ≤.10.

CONCLUSIONS

Three years after thinning and fertilization in a 30-year-old bottomland oak stand, few differences were found in the regeneration density for all species, density of oak species, and height development of oak seedlings between treatments. The regeneration pool, especially seedlings < 1 foot tall, consisted of over 2,000 spa with about 75 percent of these stems consisting of oak species. The total regeneration pool is developing as evidenced by the increased density of the larger size classes over time, but a possible problem in this stand is the development of shade-tolerant species in the larger size classes, e.g., American hornbeam and deciduous holly. Without silvicultural intervention these midstory species, along with the hickory species, may hinder future development of the oak reproduction. The size of the oak reproduction is increasing but at a slower rate compared to the other species. Future thinnings, while needed to maintain or increase the diameter growth of desired crop trees in the overstory, should also increase light availability to developing oak reproduction.

Establishment and development of oak regeneration following intermediate stand treatments, such as thinning, may be one way to reduce current oak regeneration problems. Hodges (1987) stated "... the answer to the question of how to insure adequate oak regeneration in bottomland hardwood stands is not the development of some radically new method of cutting, but the recognition that all cutting operations in the stand, from the very first, should have as one of their objectives the creation of an environment, largely light conditions, favorable for oak regeneration." While growth and development of the residual stand is the primary objective of intermediate treatments, establishment and development of oak regeneration should be viewed as an important secondary objective. Future thinnings in the present study will promote the establishment of more oak seedlings, especially as the stand matures and acorn production increases. These thinnings will also benefit the development of advance oak reproduction, possibly negating the need for midstory competition control as currently recommended in mature bottomland oak stands. Development of an advance oak reproduction pool during intermediate treatments should give the forest resource manager more options when the decision is eventually made to regenerate the stand. These options include the development of two-aged stand structures and even the possibility of developing uneven-aged oak stand structures. This increased flexibility afforded the forest resource manager should result in greater oak sustainability in bottomland hardwood stands.

ACKNOWLEDGMENTS

We thank the Arkansas Forest Resources Center and Temple-Inland Forest Products Corporation for providing funding and support for this project. We also thank John Hodges and Emile Gardiner for providing useful comments on earlier versions of this manuscript.

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SPROUT SINGLING IN NORTH ALABAMA HARDWOODS

Kozma Naka and Philip G. Cannon[1]

Abstract—Many commercial hardwood species grow quite well in northern Alabama and most regenerate by stump sprouts after harvest. The number of sprouts on a stump depends on several factors such as species and stump size. To determine if the practice of singling (removing all but the single best sprout from a stump) might be a means of accelerating the growth rate of one stem from each stump, 145 pairs of stumps were chosen at 4 different clearcut areas on a forest industry tract in Lawrence County, AL. For each pair of stumps, one randomly selected stump was "singled," while the other had no sprouts removed. Measurements taken 1 and 4 years later indicated that the sprouts of several species had very strong initial responses in diameter growth as a result of singling, especially the sprouts of the older stumps growing on moister sites.

INTRODUCTION

The extent of the forest land in northern Alabama is 2.28 million acres or 51 percent of the total land area. About 60 percent of the total forest area is of oak-hickory type (Hartsell and Vissage 2001). Many hardwood species sprout profusely from the stump following tree harvesting. In many north Alabama clearcuts, especially those on sites with northern exposure, these sprouts are an important source of forest regeneration (Dubois and others 1997). In this experiment the growth rates of single stump sprouts, liberated by cutting all but the best sprout on stumps, were compared with the growth rates of paired untreated stumps. The intent of the study was to test the hypothesis that single sprouts were more likely to have higher rates of growth than untreated sprouts.

SITES

In the fall of 1998, four clearcut areas were chosen for this study. They were all located on a forest industry tract in Moulton Valley just north of the William B. Bankhead National Forest (Lawrence County, AL). This area is part of the Appalachian Plateau Physiographic Province, Cumberland Plateau Section (NRCS 1995). The soil association is Decatur-Cumberland-Colbert-Robertsville (Soil Conservation Service 1959). At higher elevations, the soils of this association are well-drained, whereas in low-lying areas they are poorly to somewhat poorly drained. Two of the areas were harvested in 1991 and the other two in 1997. No data were collected prior to clearcutting. Chainsaws and skidders were used to clearcut the areas. Site descriptions were obtained from actual observations.

Area A had a 10 percent northwesterly slope with variable but generally shallow soils (4-12 inches deep) overlying limestone. Most of the stumps were ashes (*Fraxinus spp.*); the remaining stumps included red oak (*Quercus rubra* L.) and sweetgum (*Liquadambar styraciflua* L.). This site was clearcut 7 years prior to establishment of the experiment, and the resulting sprouts appeared to develop slowly. Area B had an irregular 30 percent slope, a northerly exposure, and fairly deep clayey soils overlying shist. About half of the stumps were maples (*Acer* spp.); the remaining stumps included chestnut oak (*Q. prinus* L.) and red oak. This site was also clearcut 7 years prior to the establishment of the experiment, but here the sprouts appeared to develop quickly, especially in coves (sites on the concave sections of the topography).

Area C was located on a bottomland site (5 percent slope) with deep clayey soils. Sweetgum was the dominant species; other stumps included maples, elms (*Ulmus* spp.), blackgum (*Nyssa sylvatica* Marsh.), and black cherry (*Prunus serotina* Ehrh.).

Area D was located on a tableland (upland) site with slopes of 0-5 percent and deep soils. This site was dominated by white oak (*Q. alba* L.) and chestnut oak. The remaining stumps were blackgum and maples. Areas C and D were clearcut 1 year before the establishment of the experiment. Sprouts appeared to develop quickly on both areas.

METHODS

Pairs of stumps were chosen at each of these four clearcut areas to facilitate paired comparisons. To be considered a pair, two stumps had to have the following characteristics in common: (1) species; (2) diameter of stump (within 20 percent); (3) similar number of sprouts; and (4) sprouts with similar heights. The distance between the paired stumps was no more than 30 feet in order to ensure that they were growing on similar sites and that they were easy to find for remeasurement.

One hundred and forty-five pairs of stumps were selected for these experiments (mid-winter 1998). The diameters of all stumps were measured, the number of sprouts on each stump was counted, and the diameters and the heights of the three largest sprouts on each stump were measured. Sprout diameter was measured to the nearest 0.1 inch at a height 2 inches above the sprout's point of contact with the stump and in the same direction as the stump's radius. One of the stumps of each pair was randomly selected for singling which involved removing all of the sprouts except

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

the one in the highest competitive position based on height and form (generally the largest and straightest). The untreated stump of that pair had no sprouts removed.

A Stihl F5-108 brushcutter was used to cut the sprouts ≤ 2 inches in diameter. This machine had a circular saw on an extended arm (fig. 1). The Sthil F5-108 was comfortable to hold; the strap balanced the load evenly, and the machine could easily be operated all day (no crouching). However, because of the length of the extended arm, it was somewhat cumbersome to use where vegetation was thick, especially in the presence of vines. Also, sprouts ≥ 2 inches were difficult to cut with the F5-108 due to blade pinching, vibration, and engine slowing.

For sprouts ≥ 2 inches in diameter at the base, a Sthil 025 chainsaw was used (fig. 2). The chainsaw required more strength to operate over a long period, and was probably riskier to operate because the cutting parts were held much closer to the body. However, the chainsaw was far more maneuverable in thick brush and permitted cutting of sprouts flush with the stump. The chosen sprouts were marked with aluminum tags. They were also flagged to facilitate their relocation (fig. 3). The time spent selecting and removing sprouts and the time in transit between stumps were recorded (time in motion).

One year after treatment, the diameters of the selected sprouts of all 145 pairs of stumps were re-measured. Four years later, 69 pairs of stumps were relocated and re-measured. Growth was calculated for each sprout as the difference between the re-measured diameter (measured 1 and 4 years after the experiment initiation) and the initial diameter. Results were analyzed for each area by comparing the diameter growth means of the singled versus not-singled sprouts. Paired t-tests for heterogeneous variances, i.e. "Welch's approximate t," (Zar 1999), were used for such comparisons.

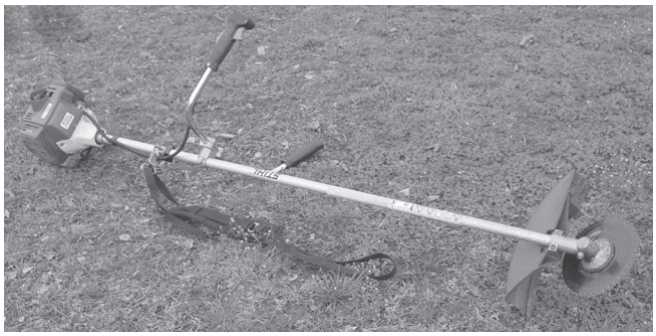

Figure 1—The Sthil F5-108 brushcutter.

Figure 2—The Sthil 025 chainsaw.

RESULTS

The growth response of 7-year-old singled sprouts was more than double the growth response of the not-singled sprouts (table 1). However, where the stumps were located on shallow soils (Clearcut Area A), sprout growth was slow; the average diameter only reached 3.7 inches. Such a site might generally be considered unproductive for forestry, and the practice of liberating sprouts probably would not be economical. By contrast, in the better site (Area B), the growth responses were the strongest both in terms of proportion and in terms of actual amount of diameter growth. Moreover, the possibilities of re-sprouts providing significant competition appeared to be minimal.

Growth response of sprouts that had been singled 1 year after clearcut was slightly more than the growth response of the not-singled sprouts. However, the strongest response was in the first year after singling these young sprouts. Four years after singling, the differences in diameter growth between singled and not-singled sprouts on the recent clearcut areas were almost negligible. A possible explanation for such a small difference is the heavy level of re-sprouting on the singled stumps. These re-sprouts probably diverted a large proportion of the water, nutrients and photosynthates that might otherwise have been translocated to the singled sprout. It seemed probable that these new sprouts would continue to compete with the singled sprout in future years.

Figure 3—Singled sprouts.

Table 1—Average diameter growth of sprouts on singled and not-singled stumps 1 and 4 years after singling in the Bankhead National Forest, AL on sites A, B, C, and D

Area[a]	Singled average growth 1998–1999	Not-singled average growth 1998–1999	Difference 1998–1999	Singled average growth 1998–2002	Not-singled average growth 1998–2002	Difference 1998–2002
A	0.3	0.2	0.1	1.2	0.5	0.7[b]
B	0.7	0.3	0.4[b]	1.8	0.9	0.9[b]
C	0.7	0.4	0.3[b]	1.7	1.4	0.3
D	0.5	0.2	0.3[b]	1.2	1.0	0.2

[a] Site definitions: A = 7-year-old stumps, bottomland, shallow soil; B = 7-year-old stumps, upland, deep soil; C = 1-year-old stumps, bottomland, shallow soil; and D = 1-year-old stumps, upland, deep soil.
[b] $p < 0.05$.

Whether sprouts from singled stumps can continue to grow into merchantable stems at a faster rate than not-singled sprouts remains to be seen and will require future measurements of these stump pairs, especially in Area A. Also, there is the possibility of sprouts developing butt rot, caused principally by *Ganoderma lucidum* (Sinclair and others 1987) originating from stumps (Tainter and Baker 1996), that should also be examined at the time of harvest.

DISCUSSION

The results of this study indicated that the rate of growth of the largest sprout on a hardwood stump can be significantly increased as a result of singling. Other studies support this finding (Johnson and Rogers 1984, Lamson 1983). However, to get the strongest and longest-lasting response, the sprouts should be allowed to develop for a number of years before the singling takes place. In this experiment, it was evident that 7 years after clearcutting was adequate time to ensure that re-sprouting would be at a minimum (fig. 4). Liberating sprouts 1 year after clearcutting did not diminish re-sprouting capabilities; not only did the stumps produce numerous sprouts, but some of these sprouts were vigorous competitors with the liberated sprouts. The optimal time to conduct sprout liberations could not be determined from this study.

Liberated sprouts on 7-year stumps may have a growth advantage due to greater access to the established root system of the stump and due to less competition above ground. Therefore, one may deduce that these liberated sprouts will continue to have a growth advantage for several additional years. Further monitoring of the growth of sprouts in Areas A and B will allow us to ascertain the duration of the liberated growth advantage.

The decision to single depends on the financial returns to be expected at time of final harvest. We hypothesize that logs developing from singled sprouts will be larger in diameter and exhibit better form than the logs developing from sprouts on stumps that were not singled. Sprouts in Areas A and B could be followed through harvest and scaled to test this hypothesis.

Figure 4— Re-sprouting (left) on a 7-year-old stump.

Although the time and motion aspects of this study were not comprehensively studied, some comments are merited. Singling was conducted in the winter because temperatures were more comfortable for outdoor work, and the vegetation was more penetrable. In re-sprouted areas such as Area A, one worker using a chainsaw could single all hardwood stumps on 2-3 acres per day. If singling was done only in the concave areas on northerly exposures, only about 10-20 percent of the topography in an area such as the Moulton Valley falls into this category. In these areas, one worker could conceivably single sprouts on 10 to 15 acres of total terrain per day.

CONCLUSIONS

This study indicated that singling, performed at some optimal time following a clearcut conferred a significant increase in diameter growth rate to the principle sprout. If this growth differential can be maintained, and if the form and health of these singled sprouts are adequate at time of final harvest, then singling may prove to be an important tool for managing hardwood forests such as those found in northern Alabama.

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PHOTOSYNTHETIC POTENTIAL OF LAUREL OAK SEEDLINGS FOLLOWING CANOPY MANIPULATION

K.W. McLeod and M.K. Burke[1]

Abstract—The theory of forest gap dynamics predicts that replacement individuals are those that can most fully use the light environment of a gap. Along the Coosawhatchie River in South Carolina, 12 canopy gaps were identified in a bottomland hardwood forest dominated by laurel oak (*Quercus laurifolia* Michaux). Each gap was enlarged to a uniform size by girdling large trees and removing smaller ones. In each gap, some plots were trenched, while some plots were left intact. Other plots, located in adjacent closed canopy forest, were treated identically. Photosynthetic light response curves of laurel oak seedlings were determined after gap enlargement. Seedling photosynthetic rates were significantly greater in gaps than under closed canopy for all light levels ≥ 150 µmol/m^2 per second. Maximum photosynthetic rates were approximately 50 percent of that for seedlings growing in full sunlight. Trenching, which eliminates root competition and increases availability to soil resources, did not affect photosynthesis. Based on these observations, laurel oak seedlings growing in gaps should have greater photosynthesis than those existing under full canopy.

INTRODUCTION

It is difficult to regenerate bottomland hardwood forests with desirable tree species following clearcutting. We have a limited understanding of conditions that improve regeneration of desired tree species, although it is generally accepted that oak reproduction should be well established before the overstory is removed (Aust and others 1985). Opening of the canopy has also been suggested to encourage growth of advance regeneration (McKevlin 1992) particularly when fairly large (≥ 1.3 cm diameter at ground level) seedlings exist (Sander 1971). However, large oak seedlings are rare in bottomland hardwood forests due to decreasing shade tolerance of developing oak seedlings (Carvell and Tyron 1961). As well, canopy openings stimulate growth of potentially competing plant species, such as intolerant trees, grasses, sedges, and forbs (Billups and Burke 1999). As a result, gaps that provide sufficient sunlight for seedling establishment and survival may be necessary to ensure sufficient oak regeneration prior to harvest.

Exacerbating difficulties in bottomland regeneration is this system's typically unpredictable hydrology. Bottomland tree species produce a mast seed crop only every few years, and when seed is abundant the site hydrology must be favorable for seed germination and seedling establishment, the occurrence of which is rare in nature. These factors combined with low light levels typical of a bottomland hardwood forest floor result in very limited growth of advance regeneration. Conversely, light is not a factor in clearcut habitats, but a rise in the water table may be expected due to a reduction in evapotranspiration demand (Sun and others 2001). Even if an adequate number of tree seedlings are established, young plants of even flood tolerant species are highly susceptible to stresses associated with flooding (Kozlowski 1997). For these reasons, advance regeneration stock may be inadequate, may not be tall enough to compete with less desirable plant species that are favored under cleared conditions, or may not be tall enough to withstand site flooding. Due to heterogeneity of environmental conditions, it is very difficult to schedule harvesting to coincide with years where site conditions are conducive to regeneration of desirable slow and intermediate tree species prior to harvest.

Although regeneration of woody plants in floodplain forests has received some attention in the literature (DeSteven and Sharitz 1997, Jones and others 1994, Streng and others 1989), little is known about the influence of canopy density on the relative success of seedlings of bottomland hardwood tree species. For example, gap theory suggests that breaks in the forest canopy may allow advance regeneration to develop at an accelerated rate due to enhanced light conditions. Gaps can either form slowly from trees dying or rapidly from stem breakage or tree fall. The extent and persistence of the gap is regulated by the size of the original canopy tree, the amount of damage inflicted upon adjacent trees, and the lateral growth rate of neighboring canopy trees into the gap. Species that can acclimate and most fully use the new light environment of a gap will have a competitive advantage and become replacement individuals in the canopy.

When gaps are formed in the forest canopy, gaps also are created in living root systems, thereby enhancing availability of soil moisture and nutrients, in addition to light. Of course, these flushes of resources may enhance growth of other plants, such as grasses, forbs and less desirable tree seedlings (Billups and Burke 1999), which can compete with seedlings of more slow-growing shade tolerant tree species. Therefore, moderately shade tolerant species would need to be released within several years if they are to survive (Johnson and Shropshire 1983) and grow to a competitive size. Under closed canopy conditions, advance regeneration can be released by removing undesirable midstory and understory vegetation (McKevlin 1992). With

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

this release, advance regeneration may have a better chance of competing with fast growing shade-intolerant species that tend to quickly become established after harvest.

After gaps are formed, leaf morphology and physiology of advanced regeneration will likely change since the light environment will be drastically altered from closed canopy conditions (< 10 percent of full sunlight) towards full light conditions (2000 µmol/m^2 per second). In some species these morphological and physiological changes can occur very rapidly (days to weeks), while for other species with more fixed growth patterns may require production of new leaves (Kramer and Kozlowski 1979, Logan 1970, Patterson 1975). Logan (1970) suggests that those species that can change rapidly would have a competitive advantage in a wide range of habitats differing in light intensity.

The present study was designed to address the following questions: (1) Do laurel oak seedlings in larger canopy gaps, such as those occurring in more mature bottomland hardwood forests, have different ability to use light than those seedlings under an intact canopy? If so, then what physiological mechanism enhances their ability to use the higher light intensity? and (2) Do belowground resources, altered by gap creation and/or trenching, affect the photosynthetic response of laurel oak seedlings?

Description of Study Site

The Coosawhatchie Bottomland Ecosystem Study site is located near Coosawhatchie in Jasper County, SC, USA (32° 40' N and 80° 55' W) and is approximately 320 ha of bottomland hardwood and swamp forest along the Coosawhatchie River. The site is owned and managed by Westvaco Corporation. The Coosawhatchie River is a fourth-order, anastomosing blackwater river that flows into the estuarine Broad River near Point South, SC. Geomorphology, soils, hydroperiod, vegetation, and vegetation dynamics of the site have been described in detail by Burke and Eisenbies (2000) and Burke and others (2003). The laurel oak community has a basal area of 40.7 ± 1.4 m^2/ha (mean ± 1 S.E.) (Burke and others 2000) and was logged as recently as 1950 (King and others 2000). Naturally-formed gaps on the site were small, with a mean of 216.1 m^2 with a median gap size of 187.8 m^2, about half to two-thirds of the natural gap size in bottomland hardwood forests of the Cache River in Arkansas (King and others 2000). In addition, total area of newly formed gaps on the Coosawhatchie site (0.02 percent) was less than the 0.5 to 1.3 percent reported for previous studies of similar forest types (King and others 2000, Qinghong and Hytteborn 1991, Runckle 1985, Van der Meer and Bongers 1996).

Few laurel oak *(Quercus laurifolia* Michaux) seedlings were found during summer of 1995. However, 1995 was a good mast year and 1996 was a dry summer, which resulted in abundant establishment of oak seedlings (Billups and Burke 1999). Seedlings were relatively more abundant in gap habitats (≥ 25/m^2), but about the same size in both habitats, probably because naturally formed gaps did not significantly increase light levels (Billups and Burke 1999).

MATERIALS AND METHODS

In July 1998, all natural gaps in the study site were geolocated, length of their axes measured, orientation of the long axis documented, and abundance of seedlings and percent cover of other vegetation was estimated.

Due to the relatively small size of gaps, it was decided for this study that these gaps must be enlarged to get more light penetration to the forest floor. Using twice tree height as the minimum gap size needed for a ground vegetation response (Collins and Pickett 1987), 12 gaps, 6 in each of 2 stands, were selected for enlarging. In late July, a 30 m line running east-west was established with the original gap-making tree in the center. Using this tree as center and the established line, a half circle with a 15 m radius south of the line was marked as the area in which to kill/remove the remaining midstory and overstory. Midstory trees were cut off at ground level and removed, while canopy trees (d.b.h. ≤ 30 cm) were girdled twice each. Gap size was now approximately 350 m^2. Enlarging the gap to the south allowed for the maximum light penetration due to the solar angle.

Four 1 m x 1 m subplots were established at random distances along the east-west line in each gap, two subplots east of center and two west. Four additional subplots were established 50 m from the midpoint of the gap edge in a random direction to establish paired non-gap plots for each gap. Non-gap areas were under full canopy cover. One subplot on either side of the gap-making tree or non-gap location was randomly chosen for trenching to eliminate root activity of midstory and overstory trees. In August, 1998, using a power trencher, 30-cm-deep trenches were dug approximately 25 cm outside the actual 1 m x 1 m subplot to minimize edge disturbance. Aluminum flashing was inserted into the trench to a depth of 30 cm, and the trench was backfilled. A previous study had determined that almost no roots penetrated below 30 cm due to high bulk density of the lower soil. A schematic diagram of a gap with associated subplots in shown in figure 1.

Seedlings were left to acclimate to the new light conditions during the rest of the 1998 growing season. The relationship between light intensity and photosynthesis was determined for a selected laurel oak seedling in each subplot on July 7, 8, 9, or 27, 1999. Seedlings in all combinations of trench/no trench and gap/no gap, associated with an individual gap were measured on a single day, but four days were required to measure seedlings in all gaps. Photosynthesis, transpiration, stomatal conductance, and internal leaf CO_2 concentration were measured with a LI-COR 6400 Portable Photosynthesis System using the LightCurve automatic program at light intensities of 1200, 900, 600, 300, 150, and 75 µmol/m^2 per second provided by a supplemental red/blue light source at a constant CO_2 concentration of 400 µmol/mol and a leaf temperature of 30 °C. Photosynthesis was first measured at the highest light intensity, followed by the next highest, and so forth for an individual seedling.

Twelve pairs (trench/no trench) of seedlings in gap and non-gap plots, six in each stand were measured in 1999. In late 1999, one stand was clearcut and seedling plots were

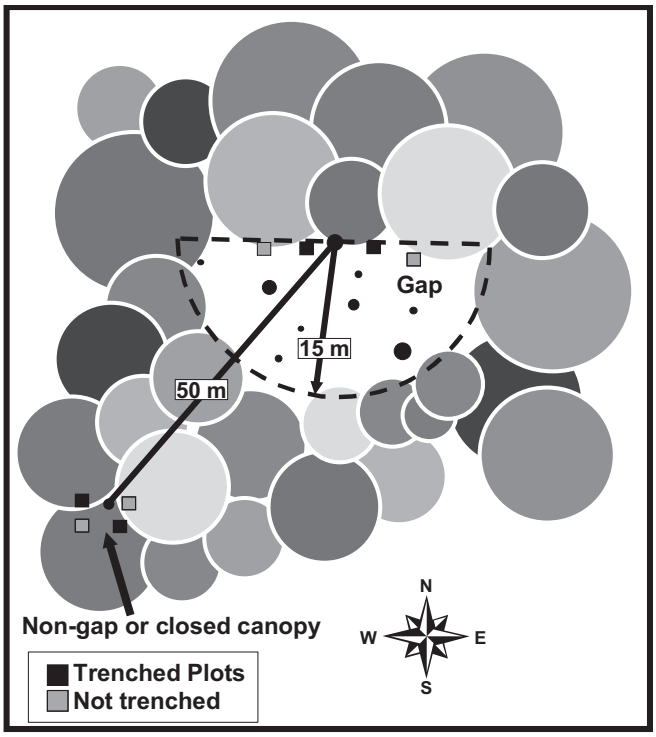

Figure 1—Schematic diagram of enlarged gap with associated subplots in the gap and intact canopy area.

destroyed and could not be relocated. In control or uncut forest stand, seedling photosynthesis was measured on October 3 and 4, 2000, but for only six pairs of plots in this one stand. Photosynthesis of four randomly selected laurel oak seedlings growing in full sunlight since the harvest in the clearcut site was also measured to determine potential maximum rates. We were unable to identify the precut light conditions of these seedlings, but they had been exposed to full sunlight for at least one growing season prior to measurement. For these open grown seedlings, photosynthesis was also measured at 1500 and 1800 µmol/m^2 per second.

To quantify ambient light conditions of the seedlings, photosynthetic active radiation (PAR) was measured at the time of each photosynthesis measurement. In August 1999, hemispherical photographs were taken 1 m above the ground at the center of the east-west line in the gap and centered among the four subplots outside the gap to determine openness of gap versus closed canopy plots. Photos were analyzed for percent canopy openness by GLA software (Frazer and others 1999). There was considerable variability of light conditions over each subplot within enlarged gaps, so on October 3, 2000 hemispherical photographs were taken at 1 m above the ground centered over each subplot.

Rates of photosynthesis, transpiration, stomatal conductance, and internal leaf CO_2 concentration were analyzed by analysis-of-variance for main effect [site (to be clearcut versus uncut), gap (in gap versus under full canopy cover), and trenching (trench versus not trenched)] and interaction effects by individual light level in each year (SAS 1999/2000).

RESULTS AND DISCUSSION

Mean gap openness in both sites were similar after enlargement of the original gaps (14.0 vs. 13.7) (table 1), although the range in individual gap openness was quite large. The most open gap was 2.5x more open than the least open gap in summer of 1999 (19.8 vs. 7.1). Expanded gaps were about the same size as natural gap size in the Cache River system (King and others 2000). Some of the more open non-gap sites had more light than gaps that had not been opened very fully. In 1999, almost 2 years after the gaps were enlarged, some trees which were girdled still had not died or fully lost their leaves. With these highly variable light levels between sites and even between gap and non-gap, acclimation of photosynthesis may be difficult to observe.

Therefore, mean canopy openness was again measured in 2000 but measurements were centered over individual gap subplots of only the control (uncut) site. The other site had already been harvested. Variability among different gaps in the 2000 data was somewhat reduced from the 1999 data and showed a similar trend among gaps in the control stand (table 2). Values indicate that the amount of light penetrating to seedlings was less in 2000 than in 1999.

Ambient light intensity was measured external to the LICOR 6400 leaf chamber with a PAR sensor. These measures may vary due to instantaneous changes in cloud cover and shadowing caused by the daily path of the sun. These

Table 1—Canopy openness[a] and light intensity in canopy gaps and in adjacent undisturbed intact canopy forest in 1999

		Canopy openness[b]		Light intensity[c]	
		mean	*range*	*mean*	*range*
Uncut (control)	Gap	14.0	7.8 – 19.8	130.3	35.6 – 225.4
Uncut (control)	Nongap	8.0	5.1 – 11.1	32.9 (73.5)[d]	24.5 – 49.0 (276.3)[e]
To be clearcut	Gap	13.7	7.1 – 19.6	141.5 (239.8)[d]	65.2 – 287.6 (731.3)[e]
To be clearcut	Nongap	11.3	9.7 – 12.6	61.8	31.8 – 134.8

[a] Openness values are percent of open sky visible.

[b] Determined by hemispherical photographs.

[c] Determined by a PAR quantum sensor (μmol/m^2/s).

[d] Mean with outlier included.

[e] Outlier value.

Table 2—Openness of the canopy gaps of the uncut area in 1999 and 2000

Gap number	Canopy openness		
	1999[a]	2000[b]	
	- - - - - - mean - - - - - -		range
1.2	10.6	8.8	7.4 – 10.7
2.3	16.8	9.6	7.7 – 9.9
3.3	7.8	6.8	6.1 – 7.5
3.5	15.8	8.5	7.8 – 9.6
4.2	13.2	9.3	7.3 – 11.0
4.4	19.8	1.6	7.5 – 13.8
Mean ± 1 S.D.	14.0 ± 4.4	9.1 ± 1.6	—

Openness values represent the relative amounts of open sky visible in hemispherical photographs.
[a] Value from a single measurement in the center of the linear portion of the semicircular plot.
[b] Values from the four subplots in each semicircular plot.

external changes would not affect photosynthesis since these measurements were made with artificial illumination. PAR measurements generally confirmed the light environments shown in hemispherical photographs. Mean light intensity in non-gap plots was 67 µmol/m^2 per second, while that in gaps was 185 µmol/m^2 per second (table 1).

Enlarged gaps were 7 times larger than gaps created in lodgepole pine forest that led to altered nutrient cycling patterns in the soil (Parsons and others 1994a, 1994b). Thus, gap enlargement and subsequent trenching should have created environments where significantly altered belowground processes were occurring.

In 1999, photosynthetic rates for laurel oak seedlings were significantly greater in gaps than under closed canopy at all light levels except for 75 µmol/m^2 per second (table 3 and fig. 2). During that same year, photosynthetic rates differed between controls, and the stand to be clearcut, except at the highest (1200 µmol/m^2 per second) light level. Difference between stands represent some differences in abiotic environment of the two stands that was not readily apparent. There was not a significant gap x site interaction, therefore main effects were not confounded.

Trenching had no effect on seedling photosynthetic rates in either year (table 3). Evidently in this fertile bottomland

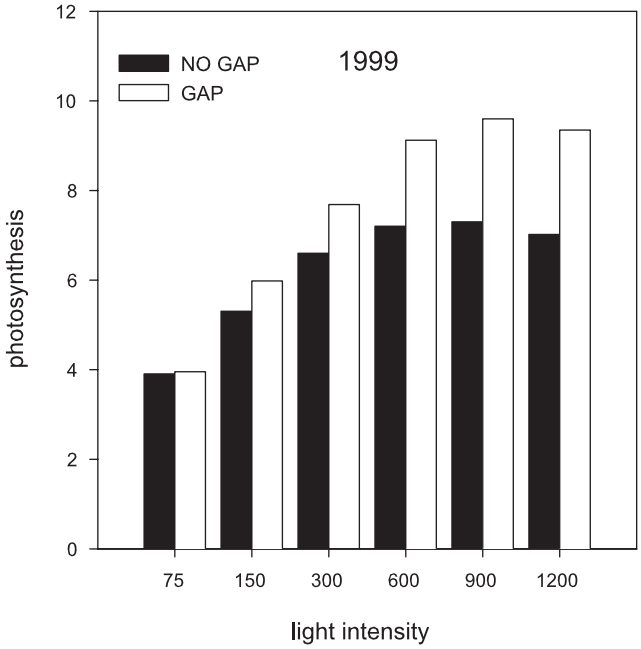

Figure 2—Net photosynthesis (µmol/m^2/s) of laurel oak seedlings at different light intensities (µmol/m^2 per second) in 1999. Seedlings had been growing in forest canopy gaps for at least 2 years (GAP), while other seedlings were growing under an intact canopy (NO GAP). Sample size was 24.

site, competition for soil nutrients and water was not great. Trenching, which both decreases root competition from other trees and increases root mortality and nutrient release, did not stimulate seedling photosynthesis. This response may have been moderated by the relative drought during 1999 and 2000 during which time root production in the laurel oak forest type was very low (Burke and Chambers 2003). This lack of response to trenching was consistent with the conservative metabolic responses usually observed for well adapted, K-selected species, in contrast to the boom-or-bust response of species growing in habitats marginal for that species (Vaitkus and McLeod 1995). No interaction terms among these factors (gap, site, or trenching) were statistically significant in either year.

Other physiological parameters which are measured include the highly related conductance, transpiration and

Table 3—Probability values for the effects of site, gap, and trenching on photosynthetic rate of laurel oak seedlings

	Light level					
	75	150	300	600	900	1200
	- - - - - - - - - - - - - - - µmol/m^2 per second- - - - - - - - - - - - - - -					
			1999			
Site	0.0001	0.0002	0.0034	0.0106	0.0364	NS
Gap	NS	0.0314	0.0102	0.0001	0.0001	0.0001
Trench	NS	NS	NS	NS	NS	NS
			2000			
Gap	NS	0.0319	0.0099	0.0076	0.0053	0.0067
Trench	NS	NS	NS	NS	NS	NS

NS = nonsignificant.
All two and three way interactions were not statistically significant.

internal leaf CO_2 concentration. As conductance increases, photosynthesis and transpiration usually increase since conductance is a measure of gas exchange rates of CO_2 and water vapor into and out of a leaf. As the rate of photosynthesis increases, internal leaf CO_2 concentration decreases since diffusion of CO_2 into the leaf can not keep up with depletion of CO_2 as it is fixed at higher photosynthesis rates. Significant differences in stomatal conductance, transpiration and internal leaf CO_2 concentration were consistent with those observed for photosynthesis (table 4).

Photosynthesis was similarly affected by seedling location within or outside of a gap in 2000 (fig. 3 and table 3). Transpiration, stomatal conductance, and internal leaf CO_2 concentration were rarely affected by seedling location in 2000 (data not shown). Absolute rates of photosynthesis between years were also similar, but these rates were approximately 50 percent of maximum photosynthesis of seedlings growing in full sun in the adjacent clearcut site (fig. 3). Trenching and the interaction of trenching with gap did not have statistically significant effects on seedling photosynthetic rates in 2000 (table 3).

Low photosynthesis rates have been linked to decreased root production and decreased survival during drought (Bourdeau and Laverick 1958, Kramer and Decker 1944). Drought in 1999 and 2000 and resultant low river water levels would have made adequate root production a necessity. Higher photosynthetic rates of seedlings in a gap would allow greater root production and greater ability to acquire water precisely at a time when water was most needed. These differences may be responsible for lower survival rate of seedlings under the closed canopy. (personal observation. M.K. Burke).

Light response curves illustrate several important general characteristics of photosynthesis. Maximum rates of photosynthesis increased as the light environment in which seedlings acclimated was greater. With this, the light levels at which light saturated photosynthesis occurred also increased (e.g., from 227 to 379 µmol/m² per second for non-gap and gap seedlings in 2000, respectively, (table 5). However, light saturation for gap seedlings was still much lower than for seedlings growing in full sun (1189 µmol/m² per second). Quantum use efficiency (determined as the slope of the increase in photosynthesis between 75 and 150 µmol/m² per second light) also increased from non-gap to gap- to full-sun-grown seedlings (table 5).

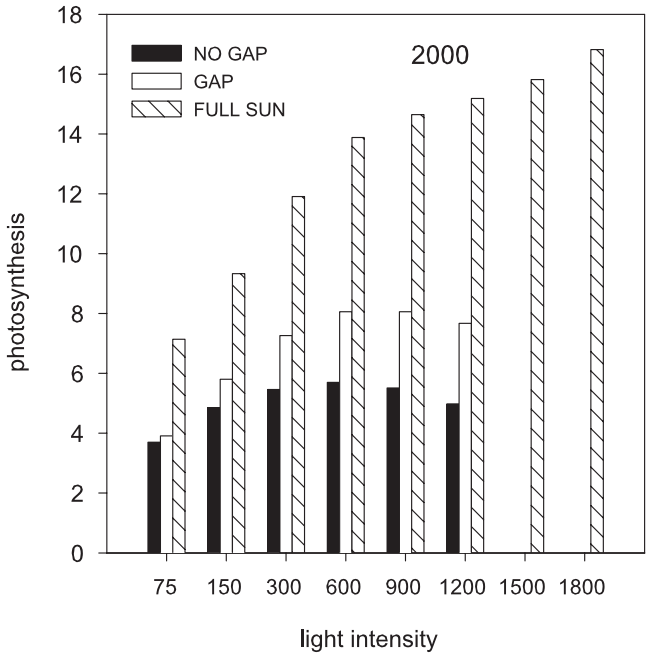

Figure 3—Net photosynthesis (µmol/m² per second) of laurel oak seedlings at different light intensities (µmol/m² per second) in 2000. Seedlings had been growing in forest canopy gaps for at least 2 years (GAP) while other seedlings were growing under an intact canopy (NO GAP). FULL SUN seedlings had been growing in a clearcut site following the 1999 growing season. Sample size was 12 for gap and no gap seedlings and 4 for seedlings in full sun. Seedlings in full sun were not compared statistically to those in gaps or under full canopy.

Table 4—Statistically significant effects on physiological parameters measured in 1999

Light intensity	Photosynthesis	Conductance	Transpiration	Internal leaf CO_2 concentration
µmol/m²/s	*µmol/m²/s*	*- - - - - - - - - -mol/m²/s- - - - - - - - - -*		*µmol/mol*
75	Site (UN > CC)	Site (UN > CC)	Site (UN > CC)	None
150	Site (UN > CC) Gap (G > NG)	None	Site (UN > CC)	None
300	Site (UN > CC) Gap (G > NG)	None	Site (UN > CC)	Gap (NG > G)
600	Site (UN > CC) Gap (G > NG)	GAP (G > NG)	Gap (G > NG)	Gap (NG > G)
900	Site (UN > CC) Gap (G > NG)	GAP (G > NG)	Gap (G > NG)	Site (CC > UN) Gap (NG > G)
1200	Gap (G > NG)	None	None	Site (CC > UN) Gap (NG > G)

UN = site to be left uncut; CC = site to be clearcut; G = Gap; NG = no-gap.
Differences were determined by three-way ANOVA for sites, gap vs. no-gap, trench vs. no trench and for all two- and three-way interactions. Only site and gap vs. no-gap significantly affected these variables.

Table 5—Summary of characteristics derived from light response curves for laurel oak seedlings

Year	Site	Light condition	Light saturation	Quantum efficiency
			μmol/m² per second	*mol CO_2/mol PAR*
1999	Both sites combined	Nongap	341 A	0.019 A
		Gap	491 B	0.027 B
2000	Control (uncut)	Nongap	227 A	0.016 A
		Gap	379 B	0.025 B
	Clearcut	Full sun	1,189	0.029

Different upper case letters within a year and characteristic indicate significant differences at the 5 percent level between seedlings in gap verses nongaps.

As the relationship between conductance and photosynthesis changes, photosynthetic capacity of seedlings will be altered. At low conductance values, photosynthesis and conductance are linearly related: photosynthesis is limited by the stomatal conductance and photosynthesis is said to be stomatal-limited. Once stomata are fully open, the rate of photosynthesis is regulated by the ability of chloroplast to fix CO_2. In this study, higher maximum photosynthesis values at similar stomatal conductances implies internal leaf modifications. Leaves of the full sun seedlings were most modified, and leaves of non-gap-grown seedlings were least modified (figs. 4 and 5). The relationship between photosynthesis and stomatal conductance for seedlings in gaps and under intact canopy were similar during the two years. At comparable conductances, photosynthesis of full-sun seedlings in 2000 was 1.7 and 1.5 times that of seedlings growing under a full canopy or in a canopy gap, respectively (fig. 5), suggesting that the ability of laurel oak to acclimate to light may be substantially greater than that documented here in experimentally enlarged gaps.

CONCLUSIONS

Exposure to higher light levels in gaps led to greater photosynthesis rates of seedlings at light levels ≥150 μmol/m² per second with apparent changes in the relationship between photosynthesis and conductance. Laurel oak seedlings, previously exposed to high light levels in canopy gaps, would have greater photosynthetic rates than seedlings from under an intact canopy and hence probably have greater size before any harvesting operations. Elimination of root competition in trenched plots did not increase seedling photosynthetic response in gaps. The initial advantage in size and photosynthetic potential could provide a competitive advantage for these seedlings following canopy disturbances that drastically change the light environment.

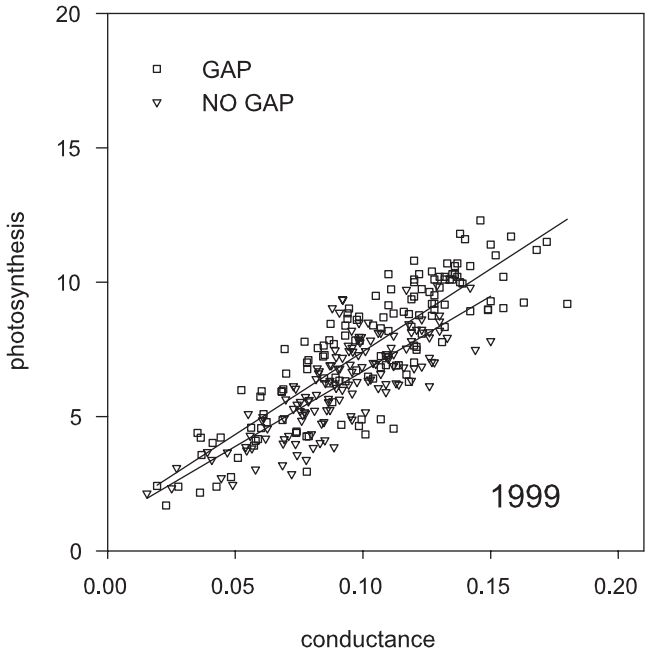

Figure 4—Relationship between net photosynthesis (μmol/m² per second) and stomatal conductance (mol/m² per second) in 1999 for seedlings that had been growing in enlarged canopy gaps for most of two growing seasons (gap) and those growing under an intact canopy (no gap).

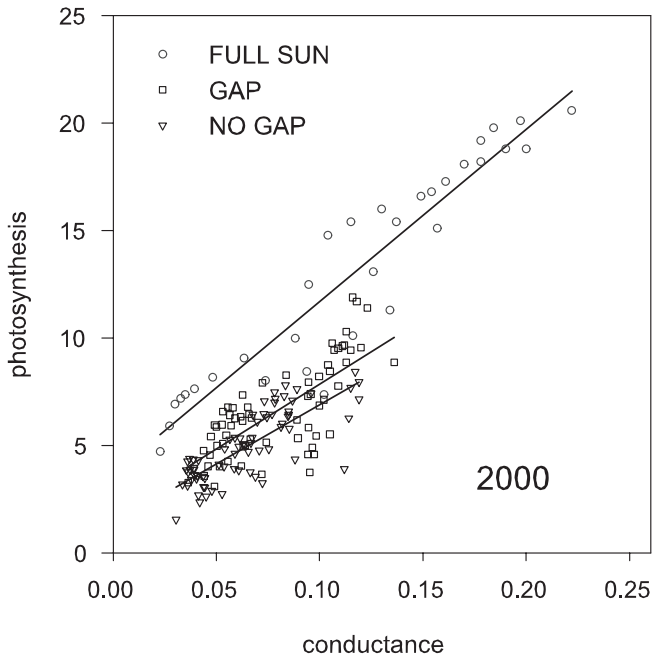

Figure 5—Relationship between net photosynthesis (μmol/m² per second) and stomatal conductance (mol/m² per second) in 2000 for seedlings growing under an intact canopy (no gap), in canopy gaps, and in full sun.

ACKNOWLEDGMENTS

Research support was provided through the study "Photosynthetic Potential of Advanced Regeneration Following Bottomland Hardwood Harvest" dated September 15, 1997 through December 31, 1999 of cooperative agreement SRS 33-CA-97-236. This research was supported by funds provided by the U.S. Department of Agriculture, Forest Service, Asheville, NC.

Westvaco Corporation (John Martin and his colleagues) has been very supportive and graciously provided use of their land for this study. Kathryn Madden, Tom Ciravolo, and Andy Harrison have provided excellent technical assistance. Manuscript reviews by Dr. R.H. Jones, Dr. M.D. Coleman, and Steve Schaff were very helpful. Financial support was provided by Financial Assistance Award Number DE-FC09-9618546 from the U.S. Department of Energy to the University of Georgia Research Foundation.

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HERBICIDE RELEASE OF 4 YEAR OLD, NATURALLY REGENERATED BOTTOMLAND OAKS – 10 YEAR RESULTS

Larry E. Nix[1]

Abstract—In 1989 two clearcut, naturally regenerated bottomland hardwood stands near the Congaree River in South Carolina were found to contain nearly 2000 red oak (*Quercus pagoda* Raf. *and Q. shumardii* Buckley) seedlings per acre. By age 4, these oak seedlings were quickly being overtopped by competitive sprouts, vines, and fast growing pioneer species. The number of remaining seedlings had been reduced to 450 per acre. In order to improve the competitive status of these desirable oak seedlings, a number of directed and broadcast pine herbicide release treatments at full and half strength were applied late in the fourth growing season. It was hoped that the overtopping competition would be inhibited or killed, but simultaneously shield the oak seedlings from the herbicides. Two year measurements indicated that oak seedling diameter growth was nearly doubled by some of the herbicides, but there was little difference in the number or canopy position of the oaks. Remeasurements 10 years after applications indicated that at least four of the simulated aerial herbicide broadcasts and one of the directed sprays resulted in 14-year-old oak saplings nearly an inch larger in diameter and three times more numerous in the dominant canopy position than those in the untreated areas. One herbicide and method of application in particular resulted in 4-inch diameter oaks, 36 feet tall with nearly 400 per acre remaining in at least a codominant status.

INTRODUCTION

In the past 30 years, oaks *(Quercus* spp.) have been decreasing in the bottomland hardwood stands of the Southern United States (Johnson 1984). Cherrybark oak *(Quercus pagoda* Raf.) and Shumard oak *(Q. shumardii* Buckl.) are two high quality bottomland oak species (Miller and Lamb 1985) that are not being replaced in these stands. The ecology and biology of bottomland oaks have been investigated to determine why the number of oaks are decreasing in new stands of the bottomland forests (Clatterbuck and Hodges 1988, Guldin and Parks 1989, Hodges and Janzen 1987, Johnson 1979). Because of their slow early growth, newly established oak seedlings cannot compete successfully with sprouts and fast-growing pioneer species. Oak seedlings often grow and die back for 4 to 6 years after germination before they reach a stage of rapid height growth.

The slow growth of oak seedlings after germination is compounded by animal predation and overtopping by briars, sprouts, and early successional trees and brush (Gingrich 1979, Hannah 1987, Nix 1989, Watt 1979). However, if released, oak seedlings can respond and achieve a dominant position in the developing canopy (Nix 1989). Some type of release of oak seedlings after clearcutting is usually needed to have oaks in the dominant canopy in a reasonable period with quality, size, and grade (Beck 1970, Hannah 1987). Release should be accomplished 3 to 5 years after clearcutting to allow the seedling oaks to quickly catch up with the other woody species on the site (Beck 1970). Early release should allow the oaks to be a dominant component of the canopy by the time the stand is 25 years old. Early release may also shorten the normal oak rotation by 10 to 15 years for quality oak products (Clatterbuck and Hodges 1988, Clatterbuck and others 1985).

Release of crop trees with herbicides has been accomplished successfully for many years in the management of pine stands (Bacon and Zedaker 1987, Clason 1978, Nelson and Cantrell 1990, Nelson and others 1985). Therefore, it should be possible to release oak seedlings with careful application of the same herbicide provided the oaks are somehow sheltered from the herbicides. During the winter of 1987 and 1988, two bottomland hardwood stands with a 40-percent oak component (basal area basis) were clearcut along the Congaree River in South Carolina. These stands apparently had a good seed crop prior to harvest, as from 3,000 to 5,000 oak seedlings per acre were established (Nix and Lafaye 1993). When first examined, in the winter of 1989, these oak seedlings were overtopped by a dense canopy of blackberry, herbaceous composites, woody seedlings, and sprouts. This study was implemented to evaluate several herbicides and application methods for releasing overtopped oak seedlings developing in dense young clearcuts.

PROCEDURE

Forty-two plots approximately 18- to 22-feet wide and 25- to 130-feet long were located along 2-foot wide transects cut through the vegetation of 3- and a 4-year-old clearcuts, approximately 1/2-mile apart in the first bottom of the Congaree River near Columbia, SC. The transects were placed where two or three cherrybark or Shumard oak seedlings in each of three height classes were found in an overtopped condition. The plots were placed at least 15 feet apart to reduce the chance of one herbicide treatment influencing any adjoining treatment. Each plot contained six to nine seedlings located along either side of the transect. Seedlings were chosen within approximately 7 to 9 feet of the transect, but at least 2 feet away so that the cut transect did not affect the seedlings' competitive status. The seedlings were selected to be approximately 6+ feet apart to accommodate the directed herbicide treatments. The length of the plot was determined by the distribution of the seedlings and the width of the plot was determined by the overspray width and the spray apparatus boom height. The

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

beginning and end of each plot center line was marked by a white, 4-foot, plastic pipe driven into the ground.

The treatment plots were blocked for replication according to preliminary estimates of total competition based on a height/distance index (Daniels 1976) on the plots (high, medium or low). Three replications of the treatments were arranged with each treatment plot randomly placed in each of the three blocks. The oak seedlings chosen for measurement were statistically similar in height on all plots. The preferred condition of the seedlings for release was overtopped, but at least 12 inches in height. Each plot contained at least two seedlings and, if possible, three seedlings in each of the three following height classes: 1-Foot Class (1 to 1.9 feet), 2-Foot Class (2 to 2.9 feet), 3-Foot Class (3 feet and taller). Each seedling chosen was marked by a wire flag and metal tag bearing an embossed coded number.

Preliminary treatments with a quick-browning herbicide in 20 percent increments of the recommended release rates for pines were applied to plots adjacent to the study area after full foliage development (midsummer) to refine the rates that were used in the treatments. The methods of treatment, herbicides, and rates which were applied in late July to early August were as follows:

1. Control—no treatment.
2. Directed (Streamline)—Application of 20 percent Garlon 4 (a triclopyr herbicide), 10 percent Cide-Kick II surfactant (JLB 1984), and 70 percent diesel fuel applied to the lower portion of all competing stems in a 3+ foot radius around the oak seedlings (Dow 1988, McLemore and Cain 1988, Yeiser and others 1989). This application was accomplished with a Solo piston backpack sprayer equipped with a D2 orifice disc tip for stream application.
3. Directed (Spot gun)—Application of Velpar L (a hexazinone herbicide) or Escort (a metsulfuron benzoate herbicide) applied in a grid pattern of six 1 mL spots placed approximately 3.5 feet from the oak seedlings to be released. The spots of Velpar L consisted of a mixture of Velpar L and water that was 50 percent of the manufacturer's product strength. The application mixture of Escort consisted of 1 ounce of Escort mixed in 2 gallons of water. Due to the fine texture of the soils on the study site, the manufacturer's rate of application for use on this texture of soil indicated that there would be a 1.5- to 2-foot non-toxic zone around the treated oak seedlings (Du Pont 1987, 1988; Rachal and others 1988). These applications were accomplished with a standard spot gun applicator calibrated at 1 mL per spot application.
4. Broadcast (Overspray)—Simulated aerial broadcast, an overspray applied with a boom apparatus, applied at 1/2 and full label-recommended application rate of commercial herbicides for releasing pines with 3.2 ounces per acre of TimberSurf 90 surfactant (0.25 percent v/v — commonly recommended rate in release of pines) (Timberland ca.1989) at 10 gallons total mix per acre (Dow 1988) for each of the herbicides in table 1. The simulated aerial broadcast spray was applied with a carbon dioxide pressurized backpack apparatus with a boom extended well above the vegetation (16 feet above ground) and equipped with a single horizontally aligned flood jet nozzle. The actual area treated was calculated by using the length of the plot, the boom height, and the nominal spray width within which competing vegetation would be uniformly treated (18 to 22 feet).

Table 1—Simulated aerial broadcast applications (oversprays) that were used at 100 and 50 percent of standard pine release rates for oak release in 3-and 4-year-old clearcut bottomland hardwood stands in South Carolina

Herbicide	Standard pine release rate
Garlon 4	1.5[a]
Escort	1[b]
Accord	1.5[a]
Velpar L	3[a]
Arsenal AC/Escort	8 / 0.25[b c]

[a] Quarts per acre.

[b] Ounces per acre.

[c] The rate of 0.25 ounces per acre of Escort remains the same for both the 100 and the 50 percent rate plots.

The spray time, spray pressure, boom height, and amount of herbicide to be used were predetermined. Measurements of the spray time and pressure were recorded for each plot so the actual rate of application could be calculated. To determine effectiveness of the release treatments after two years, herbaceous competition, woody competition, total competition, seedling height, and ground line diameter (GLD) were measured before and after treatment. Data were analyzed using a complete random block design and PC-SAS, Anova procedure. Means were tested at the 0.01 level of probability. The results of the initial reduction of competition in this study were reported in an earlier paper (Thompson and Nix 1993). For the purpose of this paper which reports 10 year response to the herbicide treatments only diameter at 4.5 feet, total height, and total number of at least codominant red oaks per plot and acre were measured. Water and willow oaks (*Q. nigra* and *Q. phellos)* were included as desirable oak crop trees along with the cherrybark and Shumard oaks previously measured.

RESULTS AND DISCUSSION

The effectiveness of any crop tree release treatment can be judged early by the subsequent tree height, diameter growth, and presence of sufficient numbers of future crop stems in the dominant canopy. In this study, oak seedling numbers, height and diameter growth 2 and 10 years after treatment were the major criteria for evaluating the effectiveness of the herbicide release treatments. After 10 full growing seasons, 4 herbicide treatments resulted in a significant increase in diameter growth of released oak seedlings (table 2). Overtopped seedlings released by the

Table 2—Ten year response of 4-year-old red oak seedlings to herbicide release in two clearcuts in Red River bottomland hardwoods in South Carolina

Treatment method	Tree per plot	Tree per acre	TPA std. dev.	D.b.h.	D.b.h. std. dev.
	- - - -number- - - -			*inch*	
AVL	4.0	170	118	3.04	0.49
AVH	8.3	365	130	3.54	0.24
AArEL	5.0	219	46	3.92	0.27[a]
AArEH	8.0	321	138	3.55	0.84
AAcH	11.7	537	223	2.86	0.29
AAcL	8.7	356	278	3.75	0.74
Control	4.7	221	171	2.45	0.04
SE	6.0	220	32	2.93	0.17
AEL	6.3	272	173	2.81	0.16
AEH	5.7	242	89	4.05	0.51[a]
AGL	7.0	266	56	4.23	0.62[a]
AGH	8.7	363	361	3.98	0.12[a]
SV	7.7	336	45	3.74	1.50
SG	9.3	391	198	3.87	1.17

TPA = tree per acre; A = at the beginning denotes aerial application; V = Velpar; Ar = Arsenal; E = Escort; Ac = Accord; G = Garlon 4; H = standard pine release rates; L = one-half rates; SE = spot applied Escort; SV = spot applied Velpar; SG = streamlined applied Garlon 4.

[a] Treatments that are significantly different from the control at the 0.01 level of *p*.

aerial broadcast application of the low rate of Garlon, the high rate of Garlon, the high rate of Escort, and the low rate of Arsenal plus Escort were significantly larger in diameter than the untreated seedlings. Numbers of at least codominant saplings, although satisfactory for future stocking at 250 per acre, did not differ from those of the control, 221 per acre. Height of released oak saplings averaged 35 feet but did not differ statistically from the 28 feet height of the control saplings.

One possible reason for the lack of significant height growth response is that the released oak saplings appeared, by casual observation, to have larger and fuller crowns than the control saplings or oak saplings that had less reduction in competition (Thompson and Nix 1993). Another reason for less height growth by released seedlings may be the vine entanglement or lack of close trainer trees in the more extreme directed treatments. The directed treatments, Velpar and Escort spot gun and Garlon streamline application were very effective where splash or flashback did not kill the released oak saplings. However, such treatments were totally impractical in the dense tangled young clearcuts. Again, from casual observation, the oak seedlings that were released enough by the directed herbicide sprays to obtain full sunlight, but that had close (within 3 feet), taller saplings, seemed to achieve more height growth than other oak seedlings.

Vines, particularly the grape (*Vitus* spp.), and honeysuckle (*Japonicum* spp.), were especially onerous; they suppressed many of the released seedlings which eventually died or lost dominance as saplings. In addition wherever vigorous loblolly pine (*Pinus taeda*) saplings and sweetgum (*Liquidambar styraciflua*) sprouts occurred in any of the treatment plots they totally dominated the canopy and suppressed even the released oak seedlings. Furthermore, it is suspected that as many as 20 percent of the taller oak seedlings, greater than 4 to 6 feet, were killed or inhibited by the herbicide overspray treatments as they projected through the sheltering main canopy at 4 years of age (Thompson and Nix 1993).

CONCLUSIONS

It is possible to release oak seedlings with careful application of selected herbicides in young (3- to 4-year-old) clearcuts without serious losses, especially if the oak seedlings are at least several feet tall and in an overtopped, sheltered condition. This overtopping, which is very common in such clearcuts, seems to shield the seedlings from a lethal amount of the broadcast herbicides. Although only 4 treatments induced a significant increase in seedling diameter 10 years after treatment, most of the 13 treatments appeared to increase diameter growth and the presence of desirable oaks in the dominant canopy. It may be too early to ascertain the full effect of this release at 14 years of age, but some of these treatments appear to have potential for establishing more oaks in the main canopy at an earlier age, thereby increasing the oak component and basal area of the young stand. It is apparent that vines must be controlled on these better bottomland sites at some time during this critical developmental period, or many of the released oak seedlings will succumb to suppression.

These are 10 year results and because of the oak developmental pattern, the codominant oak saplings need perhaps 10 more growing seasons before the full treatment effects

can be evaluated. Economic analysis of the treatments will better assess the full practicality of such herbicide release of young overtopped oaks in recently clearcut bottomland hardwood stands.

ACKNOWLEDGMENTS

The author gratefully acknowledges the assistance of former graduate student John F. Thompson who did most of the work in establishing and documenting this study in the initial 2 year measurements. Able assistance was also provided by former graduate student Charles Carlisle and current undergraduate assistant Elijah Blue Hozey in the subsequent 10 years of work. We are all grateful to the Millaree Hunt Club and Mr. Marion Burnsides, chairman, for the hospitality shown us and to the property owners, the Biedler Family, and to Angus Lafaye, consulting forester of Milliken Forestry who first called the bountiful oak regeneration to our attention.

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TIMBER HARVESTING EFFECTS AFTER 16 YEARS IN A TUPELO-CYPRESS SWAMP

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Abstract—A variety of concerns have been expressed regarding harvesting in forested wetlands. These concerns usually revolve around such issues as potential losses in site productivity, altered wetland functional processes, and development of appropriate best management practices. In 1985 a long-term study was established to evaluate harvest disturbance effects on water quality, soil properties, hydrology, and site productivity in a water tupelo (*Nyssa aquatica*) -baldcypress (*Taxodium distichum*) swamp. The study site is a deltaic red river bottomland within the Mobile-Tensaw River Delta in southwestern Alabama. After 1 year of baseline data collection, three disturbance treatments were installed in 1986: Clearcutting with helicopter removal, clearcutting with rubber-tired skidder trafficking, and clearcutting followed by complete vegetation control via glyphosate application. The three disturbance treatments were installed as three 3 X 3 Latin squares. Data were also collected from adjacent non-disturbed reference areas for comparison with disturbance treatments. Measurements of soil, water, and vegetation have been conducted at treatment ages 0-2, 7-8, 10, 12, and 16. The skidder and helicopter treatment plots have recovered since harvest due to frequent flooding, shrink-sell soils, and sediment accumulation on the site. Sediment accumulation on treatment plots increased after harvest and has returned to near pre-harvest levels at age 16. The skidder treatment has shown somewhat better recovery than the helicopter treatment, although the differences between the helicopter and skidder treatments are becoming less pronounced. As the treatment plots mature, the species composition is becoming similar to that of the reference area, and the treatment areas are expected to fully recover from disturbance.

INTRODUCTION

Forested wetlands provide a wide variety of functions and values including flood control, wildlife habitat, carbon storage, sediment removal, recreation, and timber production. Riparian wetlands affect water quality protection and enhancements; therefore, forest harvesting operations within wetlands are often more highly scrutinized than in adjacent upland areas. Wetland harvesting operations may also be within the jurisdiction of the Clean Water Act. It is very important that land managers have long-term data that can quantify the actual effects of timber harvesting in a forested wetland area. The overall purpose of this study is to quantify the long-term effects of timber harvesting on above ground biomass, sediment accumulation, and stand composition in a 16-year-old water-tupelo (*Nyssa aquatica*) - baldcypress (*Taxodium distichum*) wetland that was harvested with aerial and ground based systems.

METHODS

Study Area

The research site is located within the Mobile-Tensaw River Delta below the confluence of the Alabama and Tombigbee rivers in Baldwin County in southwest Alabama. The site consists of a two-aged stand of water-tupelo (85 percent), baldcypress (10 percent), and Carolina ash (*Fraxinus caroliniana*; 5 percent) situated within a "gum-cypress" pond. Harvesting in the delta during the past 3 centuries had resulted in two age classes at the establishment of the study in 1986, with the major component being 70-year-old trees with a few 130+ year-old residual stems remaining throughout the study site (Aust 1989, Mader 1990). Site productivity of the study area is high, with an average basal area of 330 square feet per acre and above ground biomass of 250 tons per acre in 1986. Site index was 85 feet at a base age of 50 years. The elevation of the site is approximately 10 feet above mean sea level. The site floods yearly with the wettest periods occurring during winter and spring due to lower evapotranspiration rates and increased runoff throughout the entire watershed. Floods during the rest of the year are common although less frequent than winter and spring floods. Seasonally, the water table on the site can range from several feet below the soil surface to 10 feet above the surface. Daily water table fluctuations, which can be several feet, are tidally influenced due to the close proximity of the site to the Mobile Bay and Gulf of Mexico (< 30 miles). Soils on the site are of the Levy series, a clayey, mixed, superactive, acid, thermic Hydraquent (USDA NRCS 1997). The soils contain both illite and montmorillinite clays, the latter lending to the shrink-swell properties of the soil.

Treatments

There were three disturbance treatments implemented on the study site as well as an adjacent undisturbed reference area used as an experimental control (fig 1). In 1986, all stems greater than 2.0 inches d.b.h. were felled by chainsaw on all disturbance treatment plots. Following clearcutting, all merchantable stems on all treatments were removed using a Bell 205® helicopter. Helicopter removal was the only method of timber removal on the helicopter (HELI) plots. Skidder harvesting was then simulated on skidder (SKID) treatment plots. Skidding simulation was performed to an average depth of greater than 12 inches using a Franklin 105® loaded cable skidder with 34 inch-wide rubber tires. Approximately 52 percent of the area within the SKID treatment plots was trafficked, commensurate with skidder harvesting in practice in the Mobile-Tensaw Delta at that time according to local procurement foresters (Aust 1989, Aust and Lea 1992). The third treatment involved removal of all vegetation via backpack spraying of the herbicide Rodeo (Glyphosate) for the first two growing seasons following harvest (GLYPH). The

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

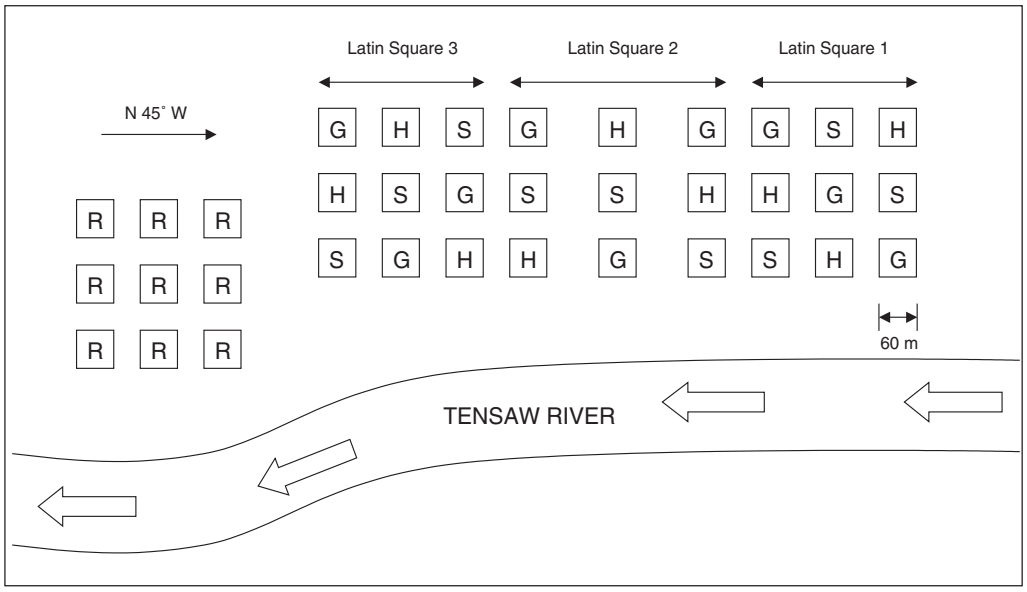

Figure 1—Mobile-Tensaw study site layout. R = Reference area; S = Skidder treatment; H = Helicopter treatment; G = Glyphosate treatment.

purpose of the GLYPH treatments was to compare the effects of vegetation versus other site factors on early site recovery after clearcutting (Aust and Lea 1991). The GLYPH plots are currently a freshwater marsh that is progressing towards a shrub-scrub, palustrine wetland. While this treatment provides an interesting study of wetland succession, it is not the focus of this paper.

Treatments were arranged in a 3 x 3 Latin Square design (Steel and Torrie 1980) to help account for potential gradients both parallel and perpendicular to the Tensaw River (fig. 1). The Latin Square design was repeated three times for a total of nine replications of each treatment. Both treatment and reference plots measured approximately 3 chains by 3 chains for an area of approximately 0.9 acre each. Reference plots were pseudo-replicated in a similar row-column pattern but could not be included in the treatment areas due to helicopter logging safety restrictions. However, the adjacent reference area and treatment area plots were compared before treatment application, and they were not significantly different from one another in terms of vegetation, soils, and hydrology. Therefore, they are suitable for use in comparison to the treatment plots.

Field Measurements and Analysis

Sediment accumulation—Nine sediment rods were installed on a grid spacing of approximately 1 chain in each of the 27 treatment plots and the 9 reference plots for a total of 324 rods in the study. The rods consist of a piece of steel rebar with a washer welded on as a benchmark for sediment accumulation. The rods were installed at the commencement of the study with the washers flush at the soil surface. The depth of sediment that accumulated (or was scoured) on the washer could then be measured periodically.

Overstory vegetation—Fixed 1/30th-acre circular overstory plots were established at all treatment and reference plot centers. All stems greater than 1.49 inches d.b.h. had the following measurements taken: species, d.b.h., total tree height, and crown class. Total biomass for each species was then determined using biomass equations developed for this site by Zaebst (1997) and Mader (1990).

RESULTS AND DISCUSSION

Stand Composition and Aboveground Biomass

There were four species that made up 98 percent of overstory species density in HELI plots and 95 percent in SKID plots at age 16: water tupelo, Carolina ash, black willow (*Salix nigra*), and baldcypress. The remainder of the species found in treatment plots included red maple (*Acer rubrum*), pumpkin ash (*Fraxinus profunda*), and water-elm (*Planara aquatica*). This is a fairly common species makeup in deep-water alluvial swamps containing tupelo-cypress stands (Larsen 1980).

One major development at stand age 16 was that black willow had started to make up a much smaller component of the HELI and SKID treatment plots (table 1). At stand age 10 (1996), HELI and SKID treatments had a black willow biomass of 13.27 and 16.41 tons per acre, respectively. By year 16 (2002), black willow comprised only 6.99 tons per acre on the HELI treatments and 9.28 tons per acre on SKID plots. Similar results can be seen in overstory species density. At age 10, HELI plots contained 436 trees per acre and SKID plots had 506 trees per acre whereas by age 16 these numbers had fallen to 173 and 223 trees per acre, respectively. Black willow is a short-lived, intolerant, pioneer species and grows aggressively from seed on disturbed wet sites (Meadows and Stanturf 1997). It is not uncommon on the research site to see 16-year-old individuals greater than 15 inches d.b.h. and 65 feet tall. However, even at age 16, the black willow component was rapidly disappearing, and the canopy gaps were being filled by the more tolerant water tupelo.

Table 1—Average density (stems per acre) and average aboveground biomass (tons per acre) of overstory trees in HELI, SKID (age 16), and REF (age 86) treatments

Common name	Genus species	HELI	SKID	REF	HELI	SKID	REF
		stems per acre			*tons per acre*		
Baldcypress	*Taxodium distichum*	90	93	36	1.30	1.71	30.04
Black willow	*Salix nigra*	173	223	—	6.99	9.28	—
Carolina ash	*Fraxinus caroliniana*	1,003	740	113	8.17	5.63	4.83
Pumpkin ash	*Fraxinus profunda*	13	13	—	0.17	0.15	—
Red maple	*Acer rubrum*	16	53	—	0.32	0.46	—
Water elm	*Planara aquatica*	6	23	—	0.02	0.09	—
Water tupelo	*Nyssa aquatica*	543	676	136	25.17	31.77	182.56
Total		1,845	1,823	285	42.14	49.09	217.43

Table 2—Average basal area (square feet per acre), average d.b.h. (inches), and average total height (feet) of overstory trees in the HELI and SKID treatments at age 16

Common name	Genus species	HELI	SKID	HELI	SKID	HELI	SKID
		square feet per acre		*inches*		*feet*	
Baldcypress	*Taxodium distichum*	7.16	7.13	3.4	3.5	24.7	26.2
Black willow	*Salix nigra*	45.40	60.23	6.7	6.8	51.7	52.2
Carolina ash	*Fraxinus caroliniana*	24.40	16.77	2.2	2.1	25.4	24.4
Pumpkin ash	*Fraxinus profunda*	0.47	0.47	2.4	2.5	30.0	29.3
Red maple	*Acer rubrum*	0.85	1.31	2.8	2.2	33.2	27.4
Water elm	*Planara aquatica*	0.18	0.71	2.3	2.9	20.0	27.9
Water tupelo	*Nyssa aquatica*	54.15	70.81	4.0	4.3	35.5	36.1
Total		132.61	157.42				

Full crown closure had occurred by age 16 in both the HELI and SKID treatments, and it appeared that the rate of biomass accumulation had started to slow. After 10 growing seasons, HELI treatments had 29.36 tons per acre and SKID treatments had 38.33 tons per acre of total woody biomass for a growth rate of 2.94 and 3.83 tons per acre per year, respectively. At age 16, HELI biomass was 42.14 tons per acre, and SKID biomass was 49.09 tons per acre for rates of 2.63 and 3.07 tons per acre per year. It is likely that competition for light due to crown closure and the mortality of fast growing black willow can account for the slowdown.

Throughout the 16 years of the study, water tupelo has had greater density, growth, basal area, and biomass in the SKID treatments than in the HELI treatments (tables 1 and 2). HELI plots contained 25.17 tons per acre of water tupelo while SKID plots had 31.77 tons per acre. Water tupelo stems were also slightly larger on average in the SKID treatment, with a mean d.b.h. of 4.3 inches and height of 36.1 feet versus 4.0 inches and 35.5 feet in the HELI treatment (table 2). However, Carolina ash, an intermediate sized and less desirable timber species, comprised a greater density and biomass in the HELI plots. The preference for water tupelo on the SKID treatment was likely due to the alterations in soil properties by skidding, effectively making those plots wetter during the early years. Saturated hydraulic conductivity, soil oxygen percentage, and redox potentials were greatly reduced in both the HELI and SKID treatments compared to the REF plots after harvest (table 3). The changes to soil properties in the HELI plots were likely due to the felling of timber during harvest onto the wet ground creating indentations in the soil surface. The greatest changes in the soil properties, however, were in the SKID plots. Rutting from the skidder and load caused a loss in soil porosity, and particularly macroporosity, thus leading to a drop in saturated hydraulic conductivity and ultimately reduced soil oxygen and redoximorphic potentials (Aust and Lea 1992). The rutting reduced both horizontal and vertical groundwater flow resulting in wetter conditions in the SKID plots. The wetter conditions were most pronounced in the first two years following harvest; however, the SKID treatments were observed to have higher water tables up to 8 years after harvest (Aust and others 1997). The initially wetter conditions following harvest favored water tupelo, the most flood tolerant species found on the site. Over time, ruts have gradually filled with sediment, and the soil has been churned due to its shrink swell properties, making the SKID and HELI plots more similar in terms of soils, hydrology, and species makeup.

Table 3—Effects of HELI and SKID disturbance treatments post-harvest (1988) on saturated hydraulic conductivity, soil oxygen, and redox potential, as compared to the undisturbed REF plots

Soil property	HELI	SKID	REF
Saturated hydraulic conductivity (*inches/hour*)	3.3	1.6	7.0
Soil oxygen (*percent*)	1.8	1.4	5.4
Redox potential (*mV*)	276	182	408

Table 4—Average and total sediment accumulation in the HELI, SKID, and REF treatments after 16 growing seasons

Sediment accumulation period	HELI	SKID	REF
	- - - - -inches per year- - - - -		
1987 – 1988	0.9b	0.6ab	0.4ab
1989 – 1993	0.6b	0.5ab	0.3a
1993 – 1996	1.0a	0.9a	0.6a
1996 – 1998	0.3a	0.3a	0.2a
1998 – 2002	0.3a	0.2a	0.2a
Total (over 16 years)	8.3b	6.7ab	4.2a

Different letters indicate significant treatment effects within each group of years at $\alpha = 0.05$.

Sediment Accumulation

Total sediment accumulation at year 16 was greatest in the HELI treatment (8.3 inches), though not significantly higher than the accumulation in SKID plots (6.7 inches; table 4). Both the HELI and SKID treatments had more accumulated sediment than the REF plots (4.2 inches), though only the HELI treatment was significantly different from the REF. Sediment accumulation was greater on treatment plots due a thick herbaceous layer that flourished following harvest and was present until crown closure when the herbaceous layer thinned out substantially (Zaebst 1997). The thick herbaceous layer essentially increased surface roughness of the treatment plots and thusly slowed down floodwaters on the site, which causes sediment deposition. Over time as the herbaceous layer was reduced, sediment accumulation in treatment plots became similar to that of the reference area.

CONCLUSIONS

Both the HELI and SKID treatments recovered well since harvest in 1986. The rapid recovery on the site was likely due to several factors. First, frequent and sustained periods of flooding brought nutrient rich sediments to the site. The flooding also helped to fill in depressions and ruts from tree felling and log skidding. Shrinking and swelling of the soil also sped site recovery by restoring macroporosity and increasing soil oxygen.

Overall, the more heavily disturbed SKID treatment was more productive than the HELI treatment and resulted in a larger component of water tupelo at age 16. The difference between these two treatments however is becoming less pronounced and may become negligible over a rotation length. The fact that the SKID treatment actually recovered better than the HELI treatment to this point was counter-intuitive. The heavy amount of disturbance that resulted from skidding was mitigated by site factors such as flooding and shrink swell soil. It cannot, however, be assumed that skidder harvesting on all wetland sites would have the same result as it had in this study. As not all wetlands are equal in their functions and recovery potential, the type of harvest method utilized should be chosen on a site-by-site basis. If a site has the potential for rapid recovery, skidder harvest should remain a viable option.

If water quality enhancement is a desired management objective in an alluvial wetland system, harvest by clearcutting should be considered. As shown in this study, clearcutting increased the amount of sediment removed from open water systems adjacent to the site relative to the reference area. Sediment scouring and accumulation are natural processes in braided river systems such as the Mobile-Tensaw River Delta. However, clearcutting and associated sediment trapping could eventually allow less flood tolerant bottomland hardwoods to become established. Small changes in elevation in bottomlands can greatly effect what species will flourish. A productive deepwater swamp that produces water tupelo and baldcypress could change to a less wet area with such species as water oak, green ash, and American elm. While this process will occur naturally, it might be accelerated by harvest, which would have implications for land managers and landowners.

Overall, growth rates, aboveground biomass accumulation, stand density and species composition in HELI and SKID treatment plots show that the site is recovering. It is expected that stands in the treatment areas will resemble the reference area in terms of species composition in the next 20 to 30 years.

ACKNOWLEDGMENTS

This study received financial support from the National Council for Air and Stream Improvement, Inc. Research Triangle Park, Raleigh, NC. The Alabama Department of Conservation and Natural Resources provided the land for the study.

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INFLUENCES OF ELEVATION ON OVERSTORY SPECIES COMPOSITION IN AN OLD-GROWTH BOTTOMLAND HARDWOOD-LOBLOLLY PINE FOREST IN SOUTHERN ARKANSAS

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Abstract—Elevation was quantified in a 16.2-ha southern Arkansas bottomland forest using surveying equipment and survey-grade GPS units. Six 500-m2 plots were established in each of three 0.5-m elevation classes. Species and d.b.h. were determined for all trees ≥ 9.1-cm d.b.h. Species importance values were calculated by plot. Twenty-four environmental characteristics were collected on site, as were soil physical, soil moisture, and soil chemical factors in the summer of 2002. The Kruskal-Wallis test of group comparisons was used for direct gradient analysis, and nonmetric-multidimensional scaling (NMS) was used for indirect gradient analysis. The direct gradient analysis identified that 30 percent of overstory species and 70 percent of environmental variables significantly differed by elevation. NMS revealed that elevation and a host of other variables were correlated to species occurrence.

INTRODUCTION

Researchers have given considerable attention to the distribution of plant communities within bottomland hardwood forests (e.g., Bell 1974; Gemborys and Hodgkins 1971; Nixon and others 1977; Titus 1990). However, studies seldom relate plant distributions to environmental conditions, and even fewer have investigated these relationships in old-growth forests (Robertson and others 1978). The Lost Forty is an old-growth bottomland hardwood-loblolly pine (*Pinus taeda* L.) forest in southern Arkansas. It offers a unique opportunity to study if and how overstory plant communities are influenced by changes in environmental conditions. Our study's objectives are to quantify elevation and environmental characteristics of the Lost Forty and to characterize overstory vegetative communities and their relationships to environmental conditions.

METHODS

The Lost Forty is located in Calhoun County, Arkansas. Dominant overstory vegetation consists of loblolly pine, sweetgum (*Liquidambar stryaciflua* L.), and oaks (*Quercus* spp.). Some trees are as large as 120-cm d.b.h. and 46-m tall with ages of more than 200 years. Wolf Creek, the largest of the small streams that meander through the area, is generally dry during the summer and autumn (June-October) and floods during the winter and spring. The soils are comprised of Guyton silt loams (frequently flooded) and Ruston fine sandy loams with 1-3 percent slopes (Gill and others 1980).

Over 1,800 X, Y, Z coordinates were established across the area using a GTS Topcon® 6000 Series Total Station. Coordinates were interpolated across the tract using ArcView® 3.2 Spatial Analyst to create a digital elevation model with a cell size of 1.5 m. The interpolation identified five 0.5-m elevation classes: ≤ 27.7, > 27.7–28.2, > 28.2–28.7, > 28.7–29.2, and > 29.2 m. However, the highest and lowest classes constituted only small portions of the tract (about 5 percent), and thus they were eliminated from the analysis. Consequently, six 500-m^2 plots were randomly located in each of the three elevation classes. Random X and Y coordinates were selected for tentative plot location, and then all interior 1.5 m^2 cells within the tentative plot were evaluated to see if they fell within the designated elevation class. If they did, the plot location was accepted; if they did not, the plot was rotated 45 degrees, and the new set of cells was evaluated. If no rotations qualified, new X and Y coordinates were selected and evaluated. This procedure was continued until six plots were randomly selected for each elevation class.

All trees ≥ 9.1 cm d.b.h. within the plots were identified by species and measured for d.b.h. in August 2002. Data were also collected on soil moisture (in May, July, and September), site and stand factors (elevation, cover of forest floor litter, and canopy cover), soil physical factors (bulk density and texture), and soil chemical factors (pH, electrical conductivity, organic matter, N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, and Na). All soil data were collected from 0-30 cm in depth.

Species importance values (IV) were calculated for each plot. Importance values was the sum of relative density, basal area, and frequency of occurrence and was expressed as a percentage. Because most vegetation data were not normally distributed, the Kruskal-Wallis test of group comparison (SAS 1989) was used to test for differences in species IV among elevation classes. Nonmetric-multidimesional scaling (NMS), a commonly used ordination technique in plant ecology (McCune and Grace 2002), was used to explore and examine patterns of species composition. Prior to ordination, species occurring on less than 5 percent of the plots were eliminated from the data. The NMS ordination used Sorenson (Bray-Curtis) distance measure, 400 iterations, random starting points, and 40 runs.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

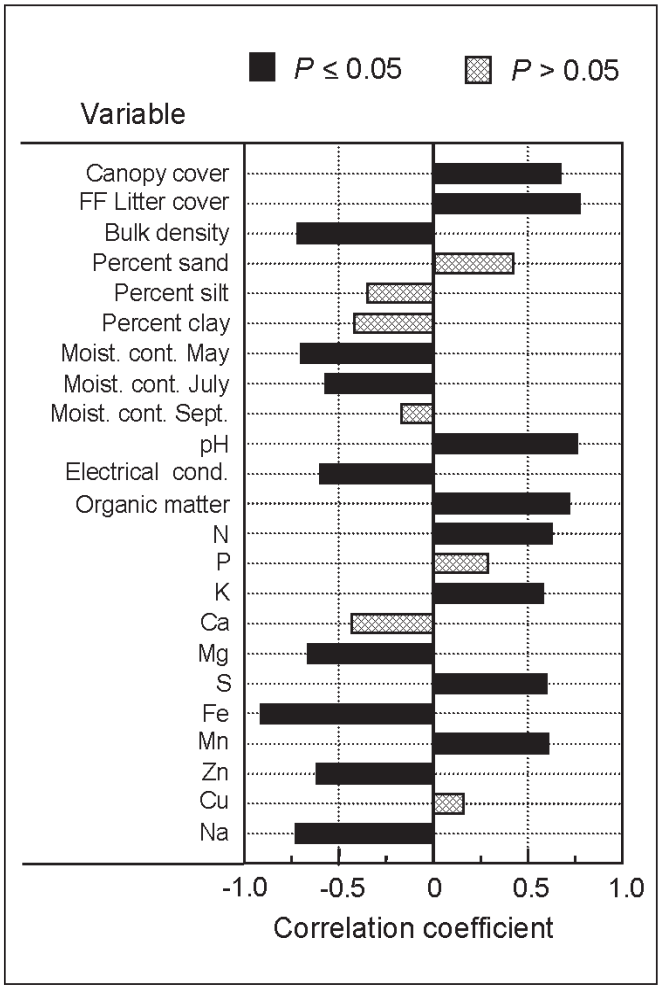

Figure 1—Correlation between elevation and other environmental variables at the Lost Forty, an old-growth bottomland forest in southern Arkansas.

RESULTS AND DISCUSSION

Elevation had a significant ($P \leq 0.05$) correlation with 16 of 23 variables (fig. 1). Variables with the strongest correlations included Fe (-0.91), forest floor litter cover (+0.77), and pH (+0.76). One-half of the significant correlations were positive, while the rest were negative. Variables with positive coefficients increased with elevation, while those with negative coefficients decreased. Only 30 percent of the variables were not significantly correlated with elevation.

Results indicated that 7 of 23 species identified in the overstory significantly differed by elevation (table 1). The IV for blackgum (*Nyssa sylvatica* Marsh.) was a maximum in the low class, and its IV decreased as elevation increased. In contrast, American basswood (*Tilia americana* L.), eastern hophornbeam (*Ostrya virginiana* K. Koch.), and American holly (*Ilex opaca* Ait.) were most common in the high class and were very uncommon in the low class. Red maple (*Acer rubrum* L.) and American hornbeam (*Carpinus caroliniana* Walt.) were at their maximum IV in the mid-elevation class. Sweetgum was an important species in all elevation classes but was at its lowest IV for the mid class.

We used NMS to produce abstract axes that arranged the Lost Forty vegetation samples in relation to each other. Axis 1 in the resulting ordination explained 74 percent in the variation, while Axis 2 explained an additional 12 percent (86 percent in total). The distance between points along the axes was an expression of the degree of similarity in species composition (fig. 2). Species such as American basswood, eastern hophornbeam, winged elm (*Ulmus alata* Michx.), flowering dogwood (*Cornus florida* L.), and sassafras [*Sassafras albidum* (Nutt.) Nees.] were clustered on the right side of the graph, which was indicative of higher elevations. In contrast, willow oak (*Quercus phellos* L.), bald cypress [*Taxodium distichum* (L.) Rich.], and persimmon (*Diospyros virginiana* L.) were clustered on the left side of the graph, which represented the lower elevations.

Ten environmental variables were strongly related with Axis 1; these included elevation (r = +0.92), Fe (r = -0.82), bulk density (r = -0.76), forest floor litter cover (r = 0.72), and May soil moisture (r = -0.71). In contrast, only percent silt (r = +0.60) and percent clay (r = -0.48) appeared to be strongly related with Axis 2. Thus, Axis 1 appeared to be a reflection of elevation and its host of associated variables, while Axis 2 appeared to be a reflection of soil texture.

Table 1—Direct gradient analysis of IV (percent) of overstory species by elevation class in the Lost Forty, an old-growth bottomland forest in southern Arkansas

Species[a]	Elevation class			P
	Low	Mid	High	
American basswood	0.0	0.0	6.2	0.035
American holly	0.6	17.6	23.7	0.002
American hornbeam	11.8	19.7	3.1	0.020
Blackgum	19.5	10.9	3.1	0.016
Eastern hophornbeam	0.0	0.0	14.4	0.001
Red maple	2.1	6.2	0.0	0.049
Sweetgum	25.7	17.6	23.7	0.002

[a] Limited to species with significant differences ($P \leq 0.05$).

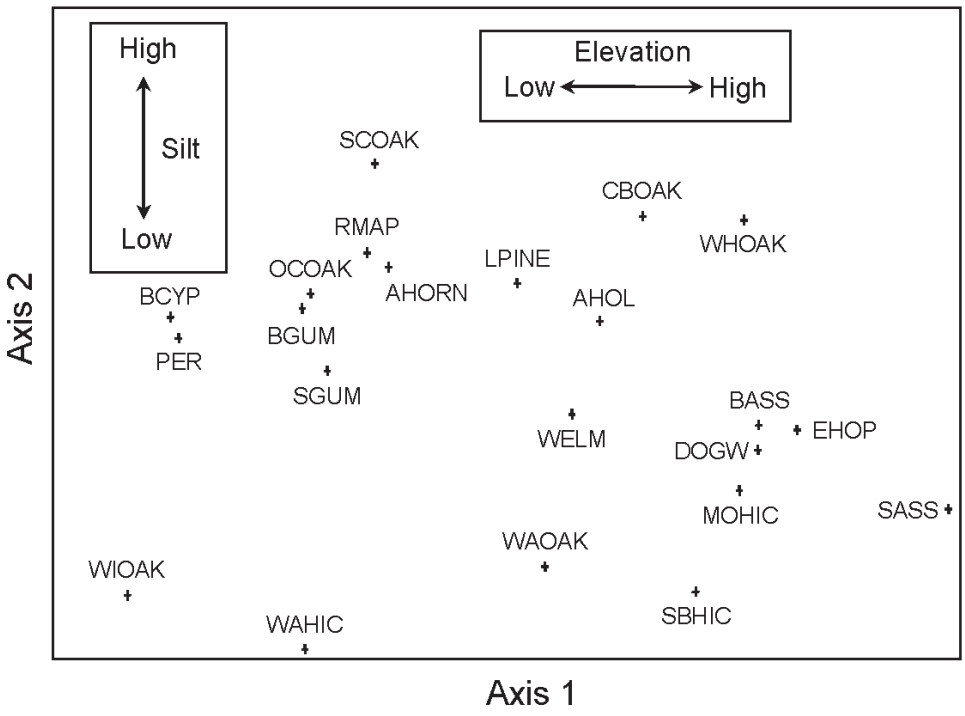

Figure 2—NMS ordination of overstory species composition in the Lost Forty, an old-growth bottomland forest in southern Arkansas. Abbreviations are: AHOL = American holly, AHORN = American hornbeam, BASS = American basswood, BCYP = bald cypress, BGUM = blackgum, CBOAK = cherrybark oak (*Quercus pagoda* Raf.), DOGW = flowering dogwood, EHOP = eastern hophornbeam, LPINE = loblolly pine, MOHIC = mockernut hickory (*Carya tomentosa* Nutt.), PER = persimmon, OCOAK = overcup oak (*Quercus lyrata* Walt.), RMAP = red maple, SASS = sassafras, SBHIC = shagbark hickory (*Carya ovata* K. Koch.), SCOAK = swamp chestnut oak (*Quercus michauxii* Nutt.), SGUM = sweetgum, WAHIC = water hickory (*Carya aquatica* (Michx. f.) Britton), WAOAK = water oak (*Quercus nigra* L.), WELM = winged elm, WHOAK = white oak (*Quercus alba* L.), and WIOAK = willow oak.

CONCLUSIONS

Within the Lost Forty, differences of only 1.5 m in elevation represented diverse landforms—ridges, flats, and transitional zones. Differences in relief, drainage, and depositional patterns resulted in pronounced soil variation. Significant differences in species composition and environmental variables were identified in three 0.5-m elevation classes. Elevation exerts its influences on species composition by affecting soil properties (chemical, physical, and moisture content) and flooding characteristics (frequency, intensity, and duration). For example, we found that forest floor litter was scoured by flooding at lower elevations, which could affect soil organic matter and associated properties. The ability to accurately and efficiently create a detailed topographic map allowed us to sample narrow elevation classes and consequently to identify strong environmental and compositional relationships. We also collected data on understory and ground flora, which are currently being analyzed; these results will provide information on the factors affecting the establishment of plant species. Results from this study suggest that differences in vegetation were primarily the result of subtle variations in elevation. Restoration or management of these forests should carefully consider these microtopographical influences.

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GERMINATION CONDITIONS FOR POISON IVY

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Abstract—Several scarification and stratification treatments were tested to optimize germination conditions for poison ivy [*Toxicodendron radicans* (L.) Kunst]. Fall-collected seeds soaked for 1 hour in water showed increasing germination with increasing stratification. Scarification with concentrated sulphuric acid for 30 minutes resulted in approximately 65 percent germination, independent of stratification. Increasing the duration of the acid treatment resulted in diminished germination. The seeds with the most natural treatments, those soaked in water for 1 hour, and those collected in February, continued to germinate beyond the standard 4-week observation period for these studies. The prolonged germination resulted in high overall germination rates, especially with longer stratification.

INTRODUCTION

Poison ivy [*Toxicodendron radicans* (L.) Kunst] is a widespread, native North American dioecious plant in the family Anacardiaceae (Gillis 1971). The plant has numerous growth forms including shrub, subshrub, or climbing vine, and can be so abundant that it is the dominant understory plant in some habitats. Poison ivy reproduces both sexually from seeds dispersed by birds or animals and vegetatively from aboveground vines, rhizomes, or root crowns. The plant is well known because the leaves and stems exude an oil, urushiol, that causes a contact dermatitis in humans.

Despite, or perhaps because of its obvious competitive nature and abundance, there is very little information about poison ivy seed germination requirements. Talley and others (1996) tested the effects of various tree extracts on poison ivy germination, but their controls only germinated successfully 24 percent of the time. Brinkman (1974) reported germination conditions for eight species of ornamental *Rhus* but not for poison ivy.

We require specific germination conditions to produce even-aged competitor plants such as poison ivy for our ecological studies of pondberry [*Lindera melissifolia* (Walt.) Blume], an endangered species in the family Lauraceae that grows in seasonally flooded bottomland hardwood habitats. In this study, we assessed the effects of several pregermination treatments reported by Brinkman (1974) to aid germination in other species of *Rhus*.

MATERIALS AND METHODS

We collected poison ivy drupes on December 19, 2001, from Leroy Percy State Park, located 5 miles west of Hollandale, Washington County, MS, and from a site on Deer Creek on the Stoneville Agricultural Research Station near Leland, Washington County, MS. Drupes were left to dry and stored in Stoneville at 68 °F until January 30, 2002, when 25 seeds from each site were planted in fresh potting soil and watered until February 22, 2002. When it became apparent that these seeds were not going to germinate, we started over with batches of 200 seeds from the original Stoneville collection and a new (late-picked seeds) collection made on February 23, 2002, from the Stoneville site. The seeds were either soaked in water for 1 hour or scarified by soaking them in concentrated sulphuric acid for 30 minutes, 1 hour, 3 hours, or 6 hours. Two groups of 50 seeds from each treatment were then germinated immediately, and 2 groups of 25 seeds from each treatment were cold stratified in wet sand at 4 °C for 30, 60, or 90 days. Seeds were germinated on Kimpak® in a Stults germination cabinet set for an 8-hour photophase, 16-hour scotophase, and a fluctuating 30 °C-daytime 25 °C-nighttime temperature regime. Seeds were allowed to germinate for 4 weeks; however, seeds in two treatments, the 1-hour soak in water and the late-picked seeds, were slow to germinate and therefore were observed for 12 weeks until there were no more visibly viable seeds.

RESULTS

We averaged the percentages of seeds that germinated for the two replicates for each trial (table 1). The paired replicates were quite consistent, with only one difference as great as 20 percent (five seeds) of a treatment. Scarification with concentrated sulphuric acid and cold stratification improved germination. Soaking seeds in sulphuric acid for 30 minutes resulted in 63- to 72-percent germination independent of stratification, but increasing exposure to acid reduced germination. Soaking seeds in acid for 3 or more hours reduced germination to negligible levels (table 1). Seeds from the original collection on December 19, 2001, soaked in water for 1 hour, and seeds collected on February 23, 2002, also soaked in water, were much more dependent on stratification for germination. Without stratification, germination was negligible, and after 4 weeks there was a general trend of increasing germination with increased stratification time. Unlike the acid-treated seeds, which completed germination or died within the standard 4-week germination period, the water-soaked seeds continued to germinate for 12 weeks, with 60- to 96-percent final germination rates. We found no apparent relationship between

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Table 1—Mean percent germination of poison Ivy seeds after 4 weeks and 12 weeks for 0, 30, 60, and 90 days of stratification

	Days stratified			
Treatment[a]	0	30	60	90
After 4 weeks				
1 hour soak in water	0	32*	22*	40*
Picked in February	1	40*	42*	72*
H_2SO_4 30 minutes	63	72	66	70
H_2SO_4 1 hour	34	62	50	52
H_2SO_4 3 hours	16	2	0	0
H_2SO_4 6 hours	3	0	0	0
After 12 weeks				
1 hour soak in water	0	82	60	70
Picked in February	1	92	96	90

[a] Treatments marked with an asterix are those that had viable seeds left after the 4-week test period and were tested for an additional 8 (12 total) weeks.

length of stratification and germination success after all the seeds had germinated (table 1).

DISCUSSION

Germination of poison ivy was clearly ameliorated by applying at least some of the pregermination treatments. Soaking seeds in sulphuric acid for 30 minutes or even 1 hour resulted in > 50 percent germination. Since germination decreased with increasing time in acid, it might be possible to get higher germination rates with shorter soak times, such as 15 minutes. Sulphuric acid presumably breaks dormancy in poison ivy seeds by eroding the brachysclerids and osteosclerids in the carpellary micropyle region as it does in *R. aromatica* (Li and others 1999). Lengthy soaking in acid (3 to 6 hours) is obviously deleterious. Perhaps most interesting is the uncoupling of scarification and stratification we observed with the acid treatment. Seeds soaked for 30 minutes in acid germinated with no cold stratification, almost as well as those with up to 90 days of cold treatment.

Talley and others (1996) soaked poison ivy seeds in acid for 1 hour and then cold stratified them in wet paper towels at 5 °C for 7 days, -5 °C for 14 days, and then another 7 days at 5 °C. Their maximum germination rate was 24.3 percent, less than half the germination rates for our 30-minute acid treatment with or without stratification. Results from the experiment by Talley and others (1996) did approximate our 1-hour acid treatment without stratification (34 percent), but germination was < 50 percent of our acid plus stratification treatments.

In our own experiment, seeds soaked in water did not germinate without cold stratification, and those picked late in February, presumably with longer cold treatment from the environment prior to collection, had higher germination rates than those stored indoors. At 4 weeks, the typical duration of a germination test, we observed that increasing cold stratification improved germination, but that many ungerminated seeds were still viable. When we extended the germination period for 8 more weeks, the percent germination exceeded that of the stratification treatment seeds. Adaptively, prolonged germination time could help poison ivy avoid unfavorable environmental perturbations. Seeds soaked in acid did not quite achieve the germination rates of water-treated seeds, but eliminating the need for stratification and synchronization of germination could be useful for mass propagation.

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Bottomland Hardwoods — Artificial Regeneration

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SURVIVAL AND GROWTH OF BOTTOMLAND HARDWOOD SEEDLINGS AND NATURAL WOODY INVADERS NEAR FOREST EDGES

John W. McCoy, Bobby D. Keeland, and Kristi Wharton[1]

Abstract—Several oak species are frequently planted for reforestation projects in the Lower Mississippi Alluvial Valley (LMAV), but the success of these plantings has been variable. The survival and growth of planted seed or seedlings are affected by a variety of factors, including competition, herbivory, site preparation, precipitation, planting stock quality, and planting techniques. We surveyed reforested fields in the LMAV to examine survival and growth of planted oaks and the occurrence of natural invaders that became established in these fields. Oak (*Quercus* spp.) densities averaged 413 stems per ha within 150 m of forest edges, as compared with 484 stems per ha between 150 to 300 m from the forest edge. Also there were higher densities of natural woody invaders near forest edges (4,234 stems per ha at 0 - 150 m compared with 2,193 stems per ha at 150-300 m). These data show that seed and seedlings proximity to a nearby forest edge has an effect on survival and growth. Since planted trees in the 0 – 150 m forest edge zone encounter high densities of natural invaders, it may be prudent to reduce the number of planted trees. Naturally occurring invaders enhance diversity and also augment depleted oak plantings near the forest edge with no added expense or effort.

INTRODUCTION

The Lower Mississippi Alluvial Valley (LMAV), an area that extends nearly 1,000 km from the confluence of the Mississippi and Ohio Rivers to the Gulf of Mexico, once supported over 10.1 million ha of wetlands (Hefner and Brown 1985, Keeland and others 1995). Greater than 80 percent of the forested wetlands in the LMAV have been lost, mostly as a result of clearing for agriculture. The wetlands that remain are highly fragmented and degraded. Forested wetlands of the LMAV continue to be lost, but attempts to reforest some of the area have been made by several state and federal agencies (Haynes and others 1995, King and Keeland 1999, Schoenholtz and others 2001). In fact, reforestation of bottomland hardwoods in the LMAV is projected to increase from the 77,698 ha planted between 1986 and 1997 to 89,009 ha between 1997 and 2008 (King and Keeland 1999). Although some reforested tracts may be as old as 30 years, many were planted less than 15 years ago (Haynes and others 1995). These reforested tracts range in size from less than 100 ha to greater than 1,500 ha (McCoy and others 2000). Few fields have been monitored for success of reforestation (Allen 1990, Schweitzer and others 1997). Very few studies have addressed oak survival and growth in the LMAV, and even fewer have addressed natural invasion of woody species onto reforested sites (Allen 1990, Allen and others 1998). Most studies of planted oak survival and growth have examined the effects of soils, site (Groninger and others 2000), water, sunlight, and other factors, but little information on the spatial distribution patterns of survival, growth, and natural invasion within these reforested fields is available.

The purpose of this analysis was to examine spatial patterns of survival and growth for planted oaks and natural woody invaders in reforested stands of the LMAV. Specifically, our objectives were to examine the effects of direction and distance from the nearest forest stand (fragment) on survival, growth, and natural invasion.

METHODS

Study sites were established in 18 reforested fields selected from 7 U.S. Fish and Wildlife Service National Wildlife Refuges in Arkansas, Louisiana, and Mississippi, 2 Wildlife Management Areas of the Louisiana State Department of Wildlife and Fisheries, and one privately owned tract (fig. 1). All fields were planted with oak species within the last 7 to 15 years. Planting densities varied for each field (Lockhart and others 2003). Most fields were direct seeded, while three fields were planted with bare rootstock.

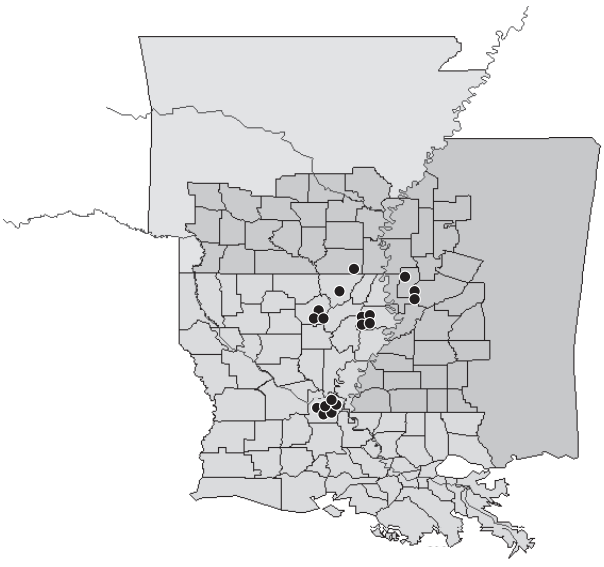

Figure 1—Map of Arkansas, Louisiana, and Mississippi showing general areas where the 18 study sites are located.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

The number of plots established within each field was determined by the size and shape of the field and the number of transects needed to adequately cover the area. About 1.3 percent of the total field area was sampled for this study. Transects were initiated at and oriented perpendicular to the field edge, which was often but not always contiguous with the forest edge. A variable distance, minimum of 75 m, was allowed between transects and between transects and field corners. Placement of transects generally depended on the direction and distance to the nearest forest fragment. We used this placement because one of our main goals was to examine natural woody invaders originating from these forest fragments. Field corners were avoided because they could be easily influenced by propagules originating from two directions.

Circular plots, each 200 m^2, were established along each transect, with the center of the first plot for each transect always established 8 m from the field edge. This insured that the plot was at the very edge of the field, yet completely within the field. Subsequent plots were spaced at 50 m intervals along the transect. The total number of plots along each transect depended on the size of the field. Plot distances referred to in this manuscript represent the midpoints of 50 m distance categories beginning at the nearest forest edge. These categories begin with 0 – 25 m because our first plot was placed at the field edge, which in many cases was immediately adjacent to the forest edge. In cases where the forest edge was at some distance from the field edge, the distance was measured and the plot placed into the appropriate distance category.

All tree or shrub stems encountered within the plots were recorded by species into four size classes: (1) 50 – 100 cm tall, (2) 100 – 140 cm tall, (3) greater than 140 cm tall but less than 2.5 cm diameter at breast height (d.b.h.), and (4) greater than 2.5 cm d.b.h. Seedlings less than 50 cm in height were not recorded. Two quadrates, each 1 m^2, located 2 m from plot center and perpendicular to the transect direction, were examined for vascular plant species and small woody seedlings. Herbaceous vegetation cover classes included, (1) 0 - 5 percent, (2) 5 - 25 percent, (3) 25 – 50 percent, (4) 50 – 75 percent, (5) 75 – 95 percent, and (6) 95 – 100 percent, for each species recorded. Woody seedlings less than 50 cm tall that were encountered in the herb subplots were counted by species.

To examine the effect of distance from forest edge on oak survival and growth and natural invasion rates, we concentrated on the zone where the majority of our plots were found. This area included the zone between 0 to 300 m from the nearest forest edge. Although a small number of our plots were as much as 1,000 m from the nearest forest edge, that data was not included in this analysis.

Differences in seedling densities between field areas less than the midpoint of the sampled distance (< 150 m) versus farther (150 - 300 m) from forest edges were tested for significance using *t*-tests under the one-way ANOVA procedure in JMP software (SAS Institute 1995). Correlation between field size to oak stem densities and proportion of the field perimeter consisting of forest to oak stem densities were also calculated using the one-way ANOVA procedure in JMP software.

RESULTS AND DISCUSSION

A total of 459 study plots were established along 67 transects at 18 sites (fields) in the LMAV. Within these plots, a total of 46 tree or shrub species, including the oaks, were recorded. The number of woody tree and shrub species per field ranged from 12 to 24 with an average of 19. Three plots did not have any woody trees or shrubs greater than 50 cm in height, while 35 plots did not contain any oak stems > 50 cm in height.

Thirty-five percent of the woody species encountered were recorded at all sites. The most common species were sweetgum (*Liquidambar styraciflua* L.), the elms (*Ulmus americana* L.*, U. alata* Michx.*,* and *U. crassifolia* Nutt.), red maple (*Acer rubrum* L.), persimmon (*Diospyros virginiana* L.), and sugarberry (*Celtis laevigata* Willd.). These species accounted for 80 percent of all naturally occurring woody stems. Additional species that were on more than 50 percent of the sites included ash (*Fraxinus* spp.), buttonbush (*Cephalanthus occidentalis* L.), mayhaw (*Crataegus spp.*), eastern baccharis (*Baccharis halimifolia* L.), locust (*Gleditsia aquatica* Marsh. and *G. triacanthos* L.), black willow (*Salix nigra* Marsh.), water oak (*Quercus nigra* L.), willow oak (*Q. phellos* L.), Nuttall oak (*Q. nuttallii* E.J. Palmer) and deciduous holly (*Ilex decidua* Walt.). All other species occurred in low numbers and had low relative frequencies for this study. The number of stems and species composition in our study was very similar to those found in a 1981 study of an 11-year-old hardwood stand on Sharkey clay soil in Mississippi (Krinard and Johnson 1981).

The most common oak species was Nuttall oak, planted on eight of the fields, with water oak and willow oak planted on four fields each. Minor amounts of overcup oak (*Q. lyrata* Walt.) and Shumard oak (*Q. shumardii* Buckl.) were also encountered. Overcup oak was planted at one site, but Shumard oak was not planted on any fields. The average density of oaks was 467 stems per ha, but the numbers were not distributed evenly among size classes. Fewer oaks were found in the smaller size classes (24 and 25 per ha for size classes 1 and 2) than in the larger size classes (150 and 268 per ha for size classes 3 and 4). The low density of the shorter oak stems was expected as these fields were planted a minimum of 7 years before our study. Although oaks have been shown in some cases to grow as little as 15 cm per year (Johnson 2002), under better conditions they can achieve as much as 137 cm in only 2 years (Burns and Honkala 1990). The largest oaks, in size class four, had measurable diameters that ranged from 2.5 cm (the smallest diameter we measured) to 9.8 cm.

The mean density of natural invaders was much higher than the density of oaks at 2,638 stems per ha. As seen with the oaks, there were relatively fewer short natural invaders with only 540 and 449 stems per ha in size classes 1 and 2. The majority of natural invaders (1,323 stems per ha) were greater than 140 cm tall but less than 2.5 cm in d.b.h.. Larger stems (> 2.5 cm d.b.h.) were less abundant, with only 326 stems per ha. These larger stems ranged from 2.5 to 6.6 cm d.b.h.

An important component of this study was the effect of distance from the nearest forest edge on the density of woody natural invader species. Within 150 m of the forest edge an average of 4,463 tree and shrub stems per ha, including oaks, was recorded. Between 150 to 300 m from the forest edge, the number of stems was much smaller, with 2,646 stems per ha. We noted a steady decrease in the number of natural invaders as distance from the forest edge increased (table 1, fig. 2), a fairly consistent pattern also reported by Allen and others (1998), McCoy and others (1998), and McCoy and others (2002). However, the pattern of decline varies greatly among species.

Near the forest edge a large number of light seeded species can become established. For example, adjacent to the forest edge we found an average of 1,581 sweetgum stems per ha, but this number declined dramatically with distance. Seed size and weight helps to determine the distance it may be disseminated into a field. Heavy seeded species such as oaks and hickories establish closest to the forest edge, while others such as hawthorn, dogwood, eastern red cedar, and baldcypress disseminate to greater distances. For several species, we noted the highest densities about 50 m away from, rather than immediately adjacent to, the forest edge. This group included hickory, dogwood,

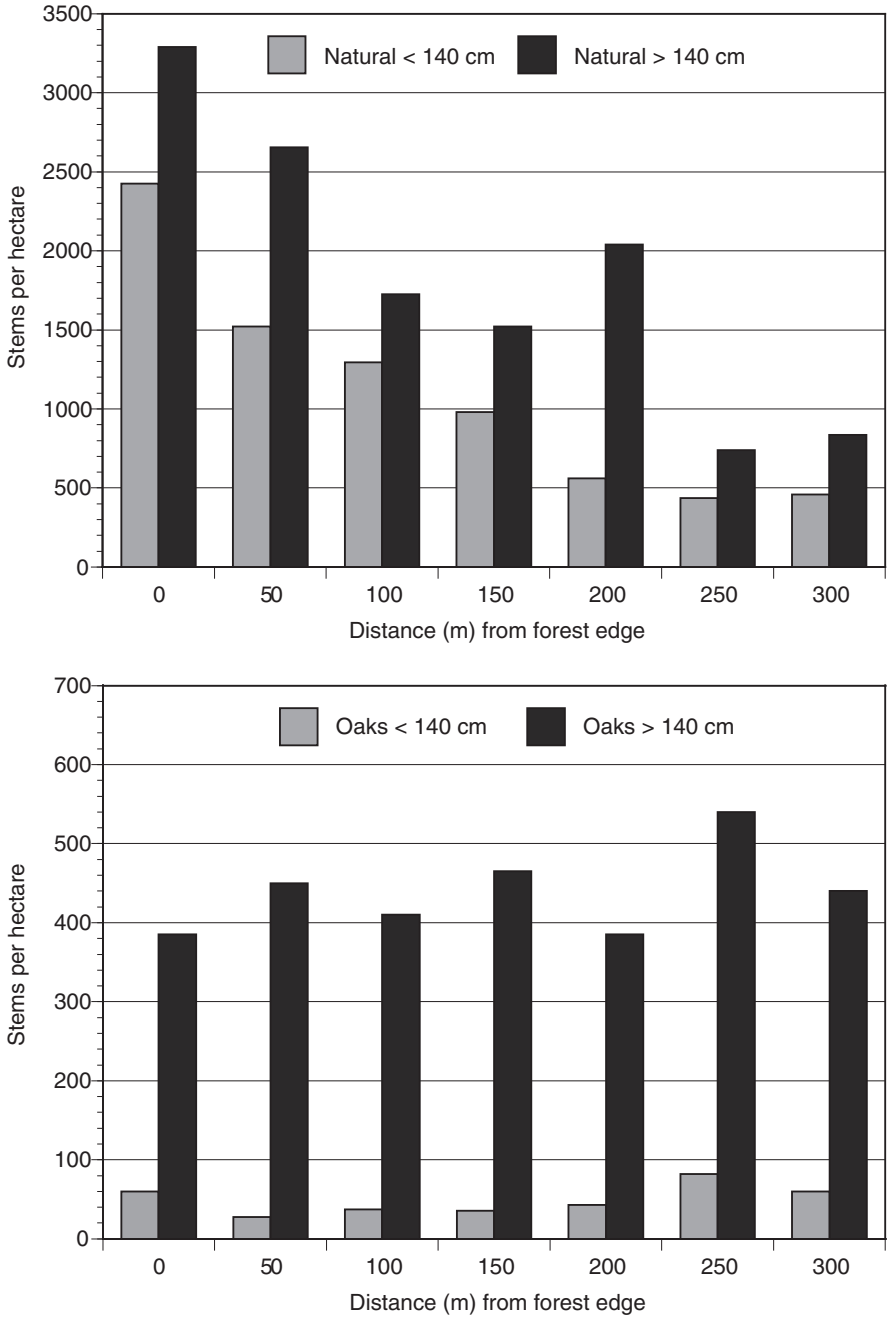

Figure 2—Stems per ha of oak and natural invader stems for < 140 cm (4.6 feet) and > 140 cm height classes.

Table 1—Density of stems/ha (> 50 cm in height) by species at the given distances from a forest edge

Species Common name	Scientific name	H or L	Distance class 0	50	100	150	200	250	300	Mean to 300	All dis
Box elder	*Acer negundo* L.	L	426	185	134	77	12	9	11	122	108
Red maple	*A. rubrum* L.	L	271	158	160	119	159	13	11	127	113
Lead plant	*Amorpha fruticosa* L.	H	176	68	96	189	71	32	175	115	88
Eastern baccharis	*Baccharis halimifolia* L.	L	363	294	308	134	709	58	174	291	254
Hickory	*Carya illinoinensis* (Wangenh.) K. Koch										
	*C. aquatica (*Michx. f) Nutt.	H	51	77	38	19	14	41	31	39	37
Sugarberry	*Celtis laevigata* Willd.	H	130	118	95	131	149	169	169	137	126
Buttonbush	*Cephalanthus occidentalis* L.	L	18	50	35	169	34	19	27	50	46
Dogwood	*Cornus stricta* Lam., *C. foemina* P. Mill.	H	66	131	113	22	33	21	8	56	66
Hawthorn	*Crataegus marshallii* Egglest.	H	172	196	149	77	46	51	47	105	95
Persimmon	*Diospyros virginiana* L.	H	436	171	173	199	127	208	92	201	182
Ash	*Fraxinus caroliniana* P. Mill.										
	F. profunda (Bush) Bush	L	768	1011	540	444	521	213	161	523	475
Honey locust	*Gleditsia tricanthos* L.										
	G. aquatica Marsh.	H	68	43	48	33	38	26	22	40	41
St. John's Wort	*Hypericum hypericoides* (L.) Crantz	H	7	14	10	2	2	0	2	5	7
Deciduous holly	*Ilex decidua* Walt.	H	198	193	160	123	93	68	97	133	114
Eastern red cedar	*Juniperus virginiana* L.	H	1	5	1	0	0	0	0	1	1
Sweetgum	*Liquidambar stryraciflua* L.	L	1,581	790	404	412	92	154	81	502	443
Loblolly pine	*Pinus taeda* L.	L	1	2	2	0	1	4	0	1	1
Water elm	*Planera aquatica* J.F. Gmel.	L	1	0	0	1	0	0	0	< 1	< 1
Sycamore	*Platanus occidentalis* L.	L	0	1	2	1	0	0	0	1	1
Cottonwood	*Populus heterophylla* L.	L	0	0	0	2	1	0	1	1	2
Mexican plum	*Prunus mexicana* S. Wats.	H	0	0	0	0	0	0	1	< 1	3
Oaks	*Quercus* spp.	H	381	420	406	455	413	622	453	450	466
Black locust	*Robinia pseudoacacia* L.	H	67	0	0	0	0	0	0	10	8
Palmetto	*Sabal minor (*Jacq.) Pers.	H	13	7	5	1	0	0	2	4	3
Black willow	*Salix nigra* Marsh.	L	14	48	12	28	36	15	48	29	27
Chinese tallow tree	*Triadica sebifera (*L.) Small	H	4	8	7	2	3	13	48	12	17
American snowbell	*Styrax americanus* Lam.	H	25	14	14	3	8	4	2	10	8
Baldcypress	*Taxodium distichum (*L.) L.C. Rich.	H	1	2	0	2	0	0	0	1	1
Elms	*Ulmus americana* L.										
	U. crassifolia Nutt.										
	U. alata Michx.	L	865	585	515	310	452	54	85	409	371
Hercule's club	*Zanthoxylum clava-herculis*	H	1	2	0	0	0	0	0	< 1	< 1
Total			6,105	4,593	3,427	2,955	3,014	1,794	1,748	3,377	3,106

H = heavy seeded; L = light seeded; Mean to 300 = the mean of 0 to 300 m; All dis = a mean for all distances and includes all distances in which a species was actually represented in our study including those outside of the 0 – 300 m range.

hawthorn, ash, and black willow. Although not tested in this study, it may be that these slightly smaller numbers immediately adjacent to the forest edge result from seed predation or herbivory of young seedlings by rabbit or deer. It may also be a result of animal behavior during or after feeding on these seed.

As distance from the forest edge increases, most wind dispersed species such as box elder, red maple, water elm, sycamore, and cottonwood decrease in density. A few wind-dispersed species, such as the elms, ash, buttonbush, and eastern baccharis, can be found in relatively high numbers at distances beyond 300 m. Anomalous patterns of density distribution, such as extremely high numbers of eastern baccharis at 200 m (table 1) can be caused by an individual field with environmental and biotic conditions that foster abnormally high numbers of a particular species.

Heavy seeded species, for the purpose of this study, are those typically dispersed by animals. Several species with seeds that are small, yet still classed as heavy seeded, such as sugarberry and Chinese tallow [*Triadica sebifera* (L.) Small], disperse to distances much greater than 300 m. Although these species are classed as heavy seeded, they are small enough for small birds to eat and disperse. We found several natural woody invaders, including persimmon, sugarberry, deciduous holly, swamp dogwood (*Cornus stricta* Lam.), locust (*Robinia pseudoacacia* L.), ash, red maple, and sweetgum, as far as 1,000 m from the nearest forest fragment. However, at these distances, stem densities averaged only 290 stems per ha.

The density of planted oak stems ranged from 0 to 2,900 stems per ha for each plot and varied significantly with distance (0 – 150 vs. 150 – 300 m) from the forest edge ($F = 18.76$, $P < 0.0001$). We counted an average of 413 oaks per ha between 0 and 150 m from the forest edge, whereas between 150 and 300 m, the count was 484 per ha (table 1). Although this difference is small, it seems to indicate a distance dependent relationship that warrants further consideration. A possible explanation for the lower density of oaks at 0 - 150 m could be herbivory of the planted oaks combined with suppression by the higher density of natural invaders establishing in this area, in a manner similar to that reported by Lorimer and others (1994). Several species of mammals, especially rabbits (*Sylvilagus floridanus*) and white-tailed deer (*Odocoileus virginianus*), use areas near the forest edge and are known to feed on oak seeds and seedlings (Castleberry and others 1999). Deer tended to stay within about 80 m of the forest edge for protective cover (Dugger and others, in press). After the competing woody species grow large enough, especially near the forest edge where densities can be quite high, the shading effect could reduce the palatability of oak leaves and perhaps reduce the herbivory pressure (Blair and others 1983).

Several additional factors could affect the spatial distribution of stem densities. First, the original planting density was variable among sites. This was probably because a combination of different oak species were planted in the various fields, local conditions may have prompted the land manager to seed the fields at higher or lower rates, and while most fields were direct seeded, a few were planted with bare-root seedlings. Within the fields, variations in soils, topography, hydrology, aspect, or spatial differences in competition or herbivory rates could also affect invasion and survival rates for natural invaders that in turn affect planted oaks (Bowers 1993).

Study fields varied in size from 7 to 150 ha. Fields were classified into (1) small (< 20 ha), (2) medium (20 – 40 ha), and (3) large (> 40 ha). The small- and medium-size fields had relatively uniform increases in oak densities as distance from the forest edge increased. Variation in topography and soils of small fields would be less than for larger ones. For large fields, the pattern of greater stem densities with distance from the forest was much more variable, possibly a result of the natural variation discussed above. However, the average oak stems per ha for small and medium sized fields was 393 stems per ha while large fields averaged 541 stems per ha. Although this difference is not significant, it does suggest larger fields may have higher densities of surviving oak stems. The opposite was true for natural invaders, with small, medium, and large fields having 5,904, 2,101, and 1,745 stems per ha, respectively. This effect was significant ($F = 5.7479$, $P < 0.0014$). As field size increased, the density of natural invader stems decreased, due to increasing distance from the nearest forest edge.

One other important factor in this study was the amount of the field perimeter made up of intact forest. The study fields were classified into three categories of contact with forest edges: (1) < 25 percent, (2) 25 – 50 percent, and (3) > 50 percent. Comparisons between these categories were not significant ($F = 1.4207$, $P > 0.2722$), but the number of oak stems per ha was, at 556, 410, and 267 in categories 1, 2, and 3, respectively. In general, smaller fields had more surrounding forest, and our results show 23 - 48 percent fewer oaks in fields with greater than 50 percent of the field perimeter in contact with forest. Conversely, natural woody invaders were more prevalent (21 – 102 percent more stems) in fields with greater amounts of forest edge. Larger numbers of invaders are expected in fields surrounded by more forest, as the trees provide a good seed source, but the reduction in survival of planted oaks with increased forest perimeter may be harder to explain. It is possible that a larger forest component provides habitat for larger populations of herbivores that feed on oak seedlings in the reforested field. A more formal evaluation of this possibility will have to wait for future studies.

The number of fields in this entire study was 18 and the total number of plots 459. Given the amount of variation in field topography, size of fields, planting techniques, preplanting preparation, seed source, and management personnel at the different locations there is a great deal of variability in the data. This variation between and within fields confounds the analysis and makes identification of significant relationships difficult. A larger sample size may have revealed more significant relationships.

CONCLUSIONS

Oaks planted in old fields are subject to a variety of factors that control their survival and growth (Allen and others 2001).

The intensity and importance of these factors, however, change through time. The herbaceous vegetation and woody vines that develop soon after field abandonment provide cover for seed and seedling predators such as rodents (*Sigmodon* spp., *Peromyscus* spp.*, Oryzomys* spp.*)* and rabbits. Herbaceous plants can also influence the survival and growth of oak seedlings (Gordon and others 1989). However, this same cover also provides perch sites that attract birds, thus encouraging natural invasion by other woody species. Wind dispersed seeds of many woody species are blown into the fields to varying distances. As the woody seedlings grow, the habitat becomes more appealing to animals that browse on the planted oaks and the natural woody invaders. This browsing reduces survival of seedlings and slows the growth of others. With increased cover, other animals use the habitat and possibly disseminate additional heavy seeded tree species. Within about 4 years (McCoy and others 1998), the oaks and natural invaders begin to overtop the herbaceous vegetation. This is especially obvious at the forest edges where natural invader densities can be very high. In many cases, the oaks will be the tallest woody species in the field since they were planted before invaders had the opportunity to become established. In some areas, such as along the forest edge, natural invaders with higher growth rates and very high stem densities can overtop and possibly decrease growth rates of the oaks. Over the next decade, the density of oaks will probably remain about the same or decrease, while the density of natural invaders will increase, especially near forest edges. This is due to a low natural invasion rate of oaks. The number of oak stems will primarily be dependent upon the initial planting, while the natural invaders continue to establish, grow, and amass by wind or animal dispersal into the field. Variables such as field size and/or forest edge contact will affect the survival and growth of woody seedlings, whether they are planted or are natural invaders. Field size may be a factor in that larger fields often have greater variability in topography and soils.

The amount of field perimeter that is contiguous with intact forest will affect the survival of oaks and the invasion rates of other woody species. The management implication of this study is that although oak densities may be reduced near forest edges, natural invasion will more than make up for the loss of stem density. Natural invasion rates will decrease beyond about 150 m from a forest edge. Although many individuals of ash, persimmon, and sugarberry will disseminate to distances greater than 150 m, the overall stem densities will be lower and additional planting may be warranted. Because of different afforestation objectives of land managers, target densities of planted species should be decided before field preparation and planting begins. Previous studies (McCoy and others 1998) have shown that sites not disked prior to planting are more diverse and develop higher densities of natural invader trees and shrubs than those disked prior to oak planting. It may therefore be sensible to plant fewer oaks within 0 - 100 m of a forest edge. This will allow for natural invaders to develop without additional competition from planted trees. In addition, small fields may not need to be planted.

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FLUSH DEVELOPMENT DYNAMICS IN FIRST-YEAR NURSERY-GROWN SEEDLINGS OF EIGHT OAK SPECIES

Shi-Jean S. Sung, Paul P. Kormanik, and Stanley J. Zarnoch[1]

Abstract—Two experiments were conducted to follow flush development dynamics exhibited by various oak species. In experiment I, southern red oak acorns were sown in mid-March 2001 at Whitehall Nursery (Athens, GA). In experiment II, acorns of black oak, cherrybark oak, Nuttall oak, Shumard oak, southern red oak, swamp chestnut oak, white oak, and willow oak were sown in December 2001 at the same nursery. Compared to the 2001-grown southern red oak seedlings, the 2002-grown southern red oak seedlings had higher germination percent and one more flush. In both years, randomly selected seedlings from each species were monitored daily for flush development. The flush elongation period (FEP), the rest period (RP), and the bud-to-bud development period (BBP) were recorded for each selected seedling. For a given flush order, RPs varied among species but FEPs did not. Consequently, BBPs varied among species. Cherrybark oak and willow oak had shorter RPs and BBPs and developed more flushes than the other oaks. A strong correlation (r = 0.94) existed between individual flush length and the maximum elongation rate in the FEPs for all eight species.

INTRODUCTION

On clearcut mesic sites, successful artificial regeneration of some oak (*Quercus*) species requires planting high-quality 1-0 nursery stocks and keeping the sites weed free for the first 2 or 3 years (Kormanik and others 1997, 1998, 2000). The species tested in such efforts included northern red oak (*Q. rubra* L.), white oak (*Q. alba* L.), southern red oak (*Q. falcata* L.), swamp chestnut oak (*Q. michauxii* Nutt.), and cherrybark oak (*Q. pagoda* Raf.). After lifting from nursery beds, 1-0 oak seedlings are graded by their height, root-collar diameter, and number of first-order lateral roots that are > 1 mm in diameter. The specified regeneration protocol utilizes only the top 50 percent of all graded seedlings (Kormanik and others 1994).

Increasing cases of oak disease and decline in the Southern United States have made restoration of oak in hardwood stands critical. Growing different oak species using this nursery protocol and understanding basic biology of individual oak species are essential in providing high-quality oak seedlings for restoration efforts. Here, we analyzed eight oak species for their germination and first-year flush development dynamics.

MATERIALS AND METHOD

Experiment I

Open-pollinated southern red oak acorns were collected from 12 mother trees in Savannah River Site forest stands (New Ellenton, SC) in the fall of 2000. These acorns were floated in water for half an hour, and those that floated were discarded. Acorns that sank were stored in plastic bags at 4 °C. In mid-March 2001 acorns were sown at a density of 54 to 57/m^2 at the Whitehall Experimental Forest Nursery (Athens, GA). The 12 half-sib families were planted by family in a randomized block design with 2 replications. One hundred and thirty acorns per family were planted in each replication. Seedlings were grown using the hardwood nursery protocol of Kormanik and others (1994). Germination was assessed on May 1 and May 18, 2001. A seed was considered to have germinated when its epicotyl emerged. In early June, 10 seedlings were randomly tagged from each family in each of the 2 replications to record daily flush elongation beginning with the second flush. The flush elongation period (FEP) began with a bud visible to unaided eyes and ended when flush length remained unchanged for 3 days. The rest period (RP) was the period between the completion of elongation and the appearance of buds beginning the next flush. The bud-to-bud development period (BBP) was the sum of the FEP and the RP.

Flush length was modeled on an individual seedling basis with the logistic equation defined as:

$$FLUSH = a / \left(1 + e^{b+cDAY}\right)$$

where

FLUSH = flush length (cm)

DAY = days since the first observation of a visible bud

a, b, c = parameters of the logistic function.

Nonlinear regression was used to estimate the parameters using PROC NLIN (SAS Institute, Inc. 1989). The instantaneous rate of flush growth on a given day was obtained by determining the slope of the specific logistic equation evaluated then. This was found by differentiation with respect to *DAY*, yielding $SLOPE = \left(-ace^{b+cDAY}\right) / \left(1 + e^{b+cDay}\right)^2$ and then substituting the appropriate day in this equation. The inflection point was where the instantaneous rate of flush growth reached its maximum and began to slow down. It was found by setting the second derivative equal to zero and solving for *DAY*, which yielded inflection point day = -b / a.

Experiment II

In fall 2001, open-pollinated southern red oak acorns were collected from 19 mother trees in Savannah River Site

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

forest stands. Six of these half-sib families were from the same mother trees used for Experiment I. Black oak (*Q. velutina* Lam.) acorns were collected from one mother tree in South Carolina. White oak acorns were collected from individuals in Virginia and North Carolina and from the Georgia State Forest Commission's Arrowhead Seed Orchards. There were 28, 22, and 14 half-sib white oak families from Virginia, North Carolina, and Georgia, respectively. Cherrybark oak was collected from one mother tree in Georgia. Mixed seedlots were collected from Texas for cherrybark, Nuttall, Shumard, swamp chestnut, and willow oaks.

In December 2001 only acorns that sank were sown by family at the same density and in the same nursery as in experiment I. Southern red oak acorns were sown in a randomized block design with two replications. Each replication had 19 families with 104 acorns per family. White oak families were randomly planted in two replications, with 26 to 52 acorns per family per replication. All Texas oaks, Georgia cherrybark oak, and black oak acorns were planted in 1 block with 182 acorns per species. All seedlings were grown with the same hardwood nursery protocol used in experiment I. Germination was scored on April 17 and May 13, 2002.

In mid-May, 24 randomly selected seedlings were tagged for each of the black, Georgia cherrybark, Texas cherrybark, Nuttall, Shumard, swamp chestnut, and willow oak species. Also, two white oak seedlings per family and six families from each of the three States were selected from each of the two replications. The 24 tagged southern red oak seedlings consisted of 2 seedlings per family and 6 families per replication. These tagged seedlings were measured daily for flush development. The logistic equation used in experiment I was used to analyze flush development dynamics.

RESULTS AND DISCUSSION

Germination

By mid-May, mean germination for southern red oak acorns was 67 percent in experiment I and 86 percent in experiment II (table 1). The six southern red oak families tested in both years had mean germination of 58 percent and 86 percent for experiments I and II, respectively. Poor germination by families 614 and 617 in 2001 was not observed in 2002. Such year-to-year variation in germination was not observed in the other four families.

By mid-May 2002, germination of black oak, Georgia cherrybark oak, and white oak from all three States was < 75 percent, while germination of the other species was ≥ 80 percent (table 2). Germination increased by > 10 percent between mid-April and mid-May for Nuttall, southern red, Virginia white, and willow oaks. In the Virginia white oak collection, most acorns seemed dry and light. Even though only the sunk acorns were sown, Virginia white oak still had low germination percent as well as a prolonged period of emergence. The negative effects of desiccation on acorn germination have been reported in different oak species (Farmer 1975, Gosling 1989, Schroeder and Walker 1987). To avoid prolonged desiccation after acorn drop, it is essential to collect acorns over short time intervals. Because of their radical protrude before sowing, white oak acorns are especially susceptible to pre- and postcollection desiccation.

Table 1—Germination of southern red oak acorns collected in 2000 and 2001 and sown in March and December of 2001, respectively, in Athens, GA

Family	05-1-01	05-18-01	04-17-02	05-13-02
			Germination percent	
520	70	78	65	83
612	72	76	76	95
614	14	14	80	90
617	39	51	85	95
618	60	74	62	88
619	55	57	56	66
543	61	62	—	—
610	64	66	—	—
611	63	67	—	—
613	85	90	—	—
615	80	85	—	—
616	76	82	—	—
517	—	—	65	86
620	—	—	74	89
621	—	—	48	60
622	—	—	77	90
623	—	—	71	83
624	—	—	62	81
625	—	—	86	93
626	—	—	65	79
627	—	—	74	88
629	—	—	79	89
630	—	—	84	93
632	—	—	87	92
633	—	—	77	87

Table 2—Germination of oak acorns collected from five States and sown at Whitehall Nursery (Athens, GA) in December 2001

Oak species; State	04-17-2002	05-13-2002
	Germination percent	
White; VA	46	63
White; NC	58	65
White; GA	70	73
Black; SC	59	60
Southern red; SC	72	86
Shumard; TX	83	86
Nuttall; TX	67	80
Swamp chestnut; TX	73	81
Willow; TX	68	80
Cherrybark; TX	91	92
Cherrybark; GA	53	54

Flush Development

Experiment I—Southern red oak seedlings began their second flush around June 20, 2001. Flush elongation periods increased by 4 and 2 days over previous FEPs, for the third and the fourth flush, respectively (fig. 1). Bud-to-bud development periods for the last flush was 5 days

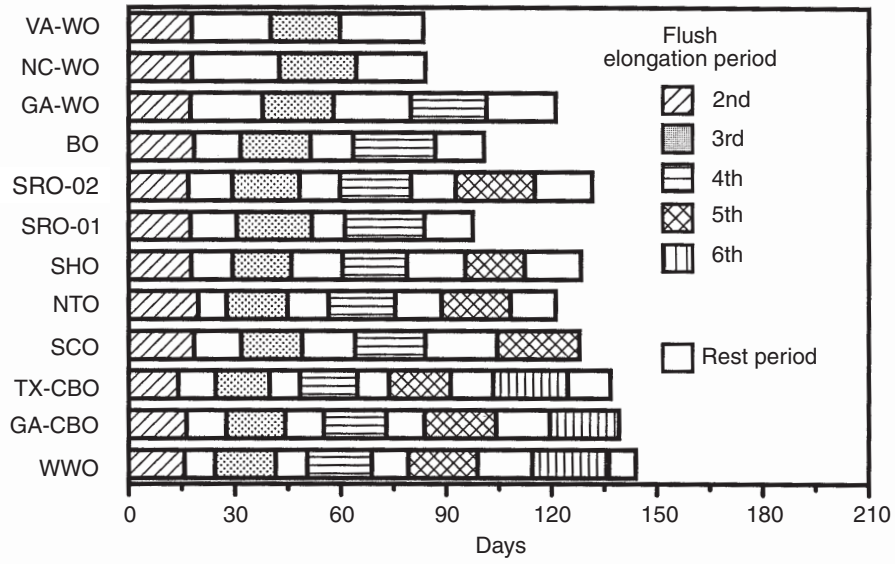

Figure 1—Duration of flush elongation period (filled blocks) and duration of the rest period (open blocks) in first-year oak seedlings from acorns collected in five States and grown in Georgia in 2002. The species included white oak (WO) from Virginia, North Carolina, and Georgia; black oak (BO); southern red oak (SRO) grown in 2001 and 2002; Shumard oak (SHO); Nuttall oak (NTO); swamp chestnut oak (SCO); cherrybark oak (CBO) from Texas and Georgia; and willow oak (WWO).

longer than for the second and the third flush. These spring-sown southern red oak grew one fewer flush than those that were winter-sown (fig. 1). Two lines of evidence support the fact that spring-sown southern red oak seedlings had a shorter growing season than the winter-sown: (1) spring-sown seedlings emerged later (table 1), and (2) spring-sown seedlings began a second flush about 3 weeks later than winter-sown seedlings. Of course, the differences in growth between winter- and spring-sown seedlings would be clearer if seedlings were evaluated in the same growing season.

Experiment II—Seedlings of Georgia and Texas cherrybark oak and willow oak began a second flush development in late May, whereas those of North Carolina and Virginia white oak did not start their second flush until the second week of June 2002. The rest of the oaks began their second flush near June 1. Within the same order of flush, little variation in FEPs was observed among species. Elongation periods for the second flushes in all species were about 17 days (fig. 1). With every next flush order, the periods increased 1 to 2 days. About 21 days were recorded for the sixth flushes in cherrybark oak and willow oak (fig. 1). The third and the fourth FEPs for the 2001-grown southern red oak seedlings took 2 more days than for the 2002-grown seedlings.

At the completion of flush elongation, most of the flush leaves were immature. Some of the top one to three leaves on each flush had not fully matured when the bud for the next flush was visible. Thus the RP had more to do with the completion of flush length growth than with leaf expansion or maturation. Our RP definition was equivalent to the sum of the linear leaf expansion stage and the lag phase in the morphological index system developed by Hanson and others (1986) for northern red oak. In contrast to the FEPs, the RPs for a given flush order varied greatly among species (fig. 1). Variation in the RPs was evident with the appearance of different flush orders at any given time after mid-July. For example, by mid-August white oak from North Carolina and Virginia had finished their third flush, which was the final flush for most of them. In the meantime, Georgia cherrybark oak and willow oak were already in the elongating phase of the fifth flush, and Nuttall, Shumard, southern red, and swamp chestnut oaks had finished the fourth flush elongation. With the exception of those occurring before the season's final flush, RPs remained constant among different flush orders of individual species (fig. 1). For year-to-year production of oak seedlings at the same nursery, duration of RPs proves to be a useful tool for early assessment of stock quality. A longer than average RP may indicate fewer flushes and less height growth, thus poor seedling quality.

Variations in BBP resulted mostly from variations in the RPs, because in any given order of flushes, the FEPs remained constant among species. Alternatively, BBP can be used to assess oak stock quality. Without measuring the length, it is impossible to note with any certainty when elongation ends. However, it is easy to observe bud appearance. Bud-to-bud periods lasted an average of 27 to 30 days for all flushes of Georgia and Texas cherrybark oak, Nuttall oak, and willow oak (fig. 1). For black oak, southern red oak from both years, and Shumard oak, BBPs were about 33 to 35 days for all flushes. Periods of 40 and 42 days were recorded for most of the white oak seedlings. The BBPs for second and third flushes of white oak from all three States were similar, although Georgia white oak had one additional flush. Therefore, it appeared that the residual effects of desiccation might affect the numbers of flushes but not the BBPs.

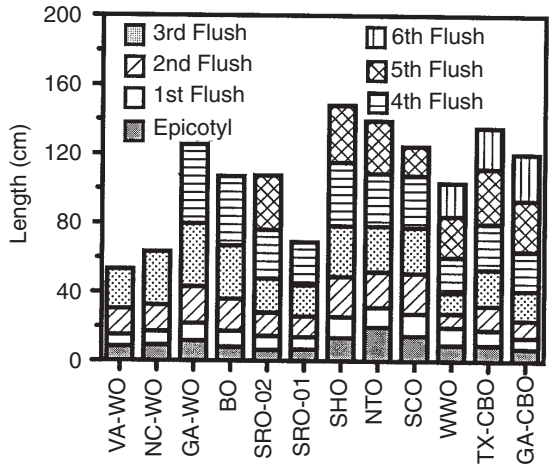

Figure 2—Individual flush lengths of first-year oak seedlings from acorns collected in five States and grown in Georgia in 2002. Species abbreviations are the same as in figure 1.

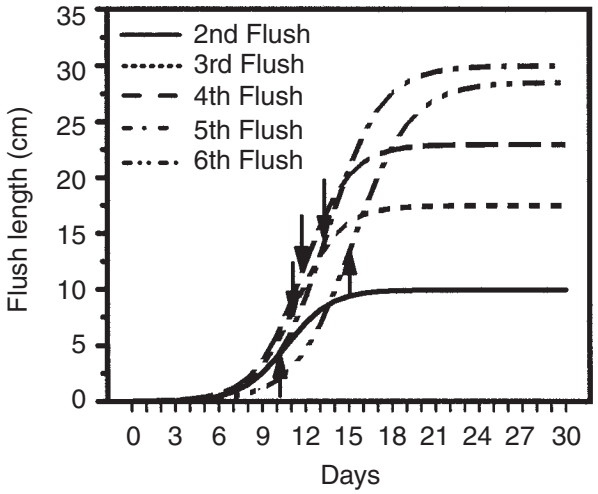

Figure 3—Logistic curves for flush length growth of the second, third, fourth, fifth, and sixth flushes of first-year cherrybark oak seedlings from Georgia. Arrows indicate inflection point day.

Generally, each flush was longer than the one before it for all oak seedlings (fig. 2). However, most last flushes occurring after mid-September were shorter than earlier flushes. For example, the fifth flush of swamp chestnut oak was much shorter than the fourth flush, and the sixth flush of willow oak was shorter than its fifth. These last flushes grew when days were shorter and day and night temperatures were lower than conditions for growth of earlier flushes. In contrast, the last flushes of white oak were the longest because they developed in summer (fig. 2). Of all species grown, Nuttall, Shumard, and swamp chestnut oaks had the longest epicotyl and first flushes. An earlier study reported correlations between first flush length and final seedling height in white oak (Sung and others 2002). Similar correlations may be established with the other oak species in future seedling growth studies. Because not all continuously monitored seedlings produced equal numbers of flushes, mean height for these seedlings were generally shorter than the sum of all individual flush lengths in figure 2. Mean height for Shumard and Nuttall oak seedlings was about 125 cm. The height of swamp chestnut, Georgia cherrybark oak, and Georgia white oak was about 110 cm. The height for black oak, Texas cherrybark oak, and willow oak was about 100 cm, and the height of North Carolina and Virginia white oak were 54 and 35 cm, respectively. Heights for the spring-sown and winter-sown southern red oak were 67 cm and 98 cm, respectively.

Logistic Equation Parameters of Flush Elongation

All flush elongations for the Georgia cherrybark oak seedlings were sigmoid curves (fig. 3) and similar to those reported earlier for white oak (Sung and others 2002). The other oak species, including southern red oak sown in spring 2001, had curves similar (data not shown) to those of Georgia cherrybark oak.

With some exceptions, inflection point days for all flushes occurred 10 to 14 days after flush bud appearance (table 3). In other words, once a flush bud began to grow, it followed a tightly controlled developmental program.

Table 3—Inflection Point Day and its slope from the logistic equation for flush length growth in first-year oak seedlings fromacorns collected in five States and grown in Athens (GA) in 2002 and from first-year southern red oak seedlings grown in 2001

Oak species; State	Flush number				
	2	3	4	5	6
	Inflection point day				
White; VA	13.4	13.6	—	—	—
White; NC	13.0	14.0	—	—	—
White; GA	12.2	13.2	12.0	—	—
Black; SC	12.4	13.6	15.8	—	—
Southern red; SC	12.6	14.0	14.4	15.9	—
2001-Southern red; SC	1.5	14.6	16.1	—	—
Shumard; TX	11.3	10.6	11.0	10.7	—
Nuttall; TX	11.6	10.9	11.1	13.0	—
Swamp chestnut; TX	1.1	11.0	12.6	15.1	—
Willow; TX	10.1	11.0	11.2	12.5	15.3
Cherrybark; TX	11.3	11.4	11.2	13.6	15.1
Cherrybark; GA	10.8	11.4	12.0	13.6	15.3
	Slope for inflection point day				
White; VA	2.5	3.4	—	—	—
White; NC	2.4	4.4	—	—	—
White; GA	3.0	4.3	5.6	—	—
Black; SC	2.7	4.4	5.0	—	—
Southern red; SC	2.2	3.2	4.4	3.9	—
2001-Southern red; SC	2.2	2.9	3.5	—	—
Shumard; TX	3.5	4.4	5.3	4.6	—
Nuttall; TX	2.4	3.9	3.9	3.5	—
Swamp chestnut; TX	3.3	4.1	3.9	2.1	—
Willow; TX	1.5	2.3	3.6	4.0	2.8
Cherrybark; TX	2.3	3.5	4.2	4.2	3.0
Cherrybark; GA	1.6	2.8	3.5	4.0	3.6

However, the inflection point slope (elongation rate) varied greatly among flushes and among species (table 3). With FEPs (fig. 1) and inflection point days (table 3) similar among species, variation in flush length (fig. 2) must have resulted from different elongation rates (table 3). The correlation coefficient between the inflection day elongation rate and flush length for all flushes of all species was 0.94. For southern red oak, the inflection point day and its slope and the flush length for the second, third, and fourth flushes were similar between two crops (table 3).

CONCLUSIONS

The lower percent acorn germination, fewer flushes, and shorter total height for the 2001-grown southern red oak as compared with the 2002 seedlings might be because the former was spring sown and the latter was winter sown. Except in some seedlings' last flushes, each oak flush had a greater maximum elongation rate and longer final length than the flush preceding it. Most species studied here had a similar FEP for a given flush order. However, the RP varied greatly among species. Except for those occurring before the last flush, the RPs remained constant among different flush orders within the same species. Cherrybark oak and willow oak, having shorter rest periods and thus shorter BBD, produced more flushes than other oaks. The less-than-satisfactory germination and growth of white oak from Virginia may have caused by excessive acorn desiccation before collection.

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HOW ARE INVESTMENT RETURNS AFFECTED BY COMPETITION CONTROL AND SOUTHERN OAK SEEDLING SURVIVAL?

Donald L. Grebner, Andrew W. Ezell, Deborah A. Gaddis, and Steven H. Bullard[1]

Abstract—Increasing numbers of landowners are establishing hardwood plantations to satisfy their management objectives. Despite a dearth of research on competition control and its effects on initial hardwood plantation survival and investment returns, this study examines alternative competition control regimes for southern oak establishment. The analysis includes estimates of land expectation value for comparing alternatives. Our results suggest that greater returns can be achieved for southern oaks during both good and bad rainfall years, using methods that maximize survival through competition control.

INTRODUCTION

Non-industrial private landowners have varied objectives for managing their timberlands in the South. With the aid of federal and state government incentive programs, more landowners are investing in the establishment of hardwood plantations. The potential for this new resource may have a significant impact on plywood and furniture industries. There have been few studies on hardwood plantations from an economic or a biological perspective. To date, relatively little information is available regarding their growth and yield and before- or after-tax returns.

An important element of any feasibility study for establishing a hardwood plantation is seedling survival. Seedling survival depends on many factors that include biological, environmental, and operational elements. Biological elements include genetics and competition with herbaceous and woody species. Environmental elements include temperature, rainfall, and other weather conditions. Operational elements include planting quality, location, timing, vegetation control, and pest control. These elements may have a positive or a negative impact on the final volume and value yield of a hardwood stand. This study focused on the influence of competition control on seedling survival and investment returns in southern oak plantations.

Numerous studies have examined the economics of hardwoods, including Deurr and Bond (1952) and Niese and Strong (1992). Studies relevant to this one include Hoover and Vasievich (1989) and Ezell and Bullard (1997). However, few studies have examined hardwood seedling survival and the impacts of different regeneration practices on investment returns. Regeneration studies include Steiner (1987) and Bullard and others (1992).

In general, these studies indicate that little has been done to evaluate the importance of competition control on investment returns for hardwood plantations. Hardwood regeneration has been examined from a financial and economic perspective, but no one has focused on expected initial survival. Goodson and Bullard (1997) indicated that few studies have been done in this area. The use of financial criteria, such as net present value and land expectation value in after-tax procedures, has been widely used in comparative analysis studies. Therefore, this study uses a similar analytical approach consistent with traditional practices but unique for its focus on expected first-year survival of oak seedlings.

Under consideration are whether competition control plays a role in seedling survival and/or whether it affects investment returns for oak plantations in the South. The oak plantations are planted on abandoned agricultural land. The study focused on competition control and its impact on first year survival of oak seedlings. Three different management practices were compared and their impacts on seedling survival and investment returns evaluated. A no site-preparation treatment was compared to those that included disking only and herbicides only. Seedling survival information was obtained from various published and unpublished sources that apply to oak stands on abandoned agricultural fields in the South.

METHODS

This study compared a base case and two alternative management regimes for controlling vegetation during stand establishment. Land Expectation Value (LEV) on an after-tax basis was used to evaluate the feasibility of these practices. Although the examples are hypothetical, scenarios reflect a realistic commercial design for the mid-South. Land expectation value models were developed on an after-tax basis. Three alternative management scenarios were also evaluated by competition control techniques and weather conditions.

The landowner was assumed to be an "investor" under the passive loss rules, who expected to generate an eventual profit from the sale of timber. The initial afforestation investment was assumed to be partially covered by a federal or state cost-share program such as the Forestry Incentives Program (FIP) or a state program such as Mississippi's Forest Resource Development Program (FRDP). Under IRC § 126, cost-share payments such as the FIP are excludable from income. In this study, the landowner was assumed to exclude all cost-share payments from income, thereby avoiding payment of income tax and

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

self-employment tax. Exclusion of income was not an option for some governmental cost-share programs such as the Conservation Reserve Program (CRP). Landowners must treat CRP rental payments and cost-share payments as ordinary income, including assessment of self-employment tax. This analysis does not apply to landowners using CRP and other similar programs ineligible for income exclusion.

The landowner is also assumed to take advantage of the investment tax credit for reforestation expenses [IRC § 48 (b) (1986)] and the accelerated amortization of reforestation expenses (IRC § 194). Investor status allows the landowner to deduct these expenses regardless of whether deductions are itemized. Since the analysis was conducted on a per-acre basis, the landowner was also assumed to have total afforestation expenses under $10,000 per year, which allows amortization of 95 percent of expenses not covered by the cost-share program.

Model Development

The after-tax analysis was conducted for comparative purposes; we followed Bullard and Straka (1998) where revenues, costs and the discount rate were adjusted to an after-tax rate. After-tax revenues were calculated by multiplying the before-tax revenue by (1-t), where t is the marginal tax rate faced by an individual. After-tax costs are calculated in the same manner if they are considered expensed. Our definition of expensed costs was one where a cost was deducted in its entirety in the year in which the cost occured. In forestry investments, reforestation expenses are typically considered capitalized costs, but the 8-tax year amortization schedule is implemented to deduct these costs earlier. The amortizable basis used in our analysis was reduced by one-half the federal investment tax credit taken.

We assumed the landowner received 50 percent cost share from a government program to establish their oak plantations, although it is not uncommon to see 40 percent in certain locales due to a high demand for these financial resources. The next step in conducting an after-tax analysis before using cash flow formulae was to convert the discount rate to an after-tax rate. We followed a procedure suggested by Bullard and Gunter (2000) which used an inflation rate. We assumed inflation to be 2.5 percent. Once all after-tax conversions were made, converted monies were discounted across time to calculate the after-tax land expectation value for each scenario. State income taxes were not considered in this analysis; the results were after-tax with regards to federal income taxes only.

Management Regimes

The economic impact of competition control on seedling survival in oak plantations was examined by comparing three alternative management regimes. Each alternative was modeled by considering both good and bad rainfall years. Good years were defined as normal rainfall conditions in the South during the months of March, April, and May with intermittent showers during the summer months; bad years were defined as below normal rainfall levels for the same time periods. In addition, we examined returns with and without re-plantings. Re-plantings were assumed to occur when seedling survival after 1 year was less than 50 percent of the original planting. An assumption made with regard to survival was that poor establishment allows adequate areas with light, water, and nutrients to justify re-planting.

Base: No site preparation—This model assumed that no site preparation was conducted and that seedlings were hand-planted directly into old fields. During good weather conditions with adequate rainfall, 60 percent survival of planted seedlings was expected. A lower survival rate of 30 percent was expected for poor rainfall years. In addition to these differing weather conditions, this regime included a re-planting scenario.

Alternative 1: Disking only—This model incorporated site preparation, consisting of disking only, with seedlings hand-planted directly into old fields. During good weather conditions with adequate rainfall, 62.5 percent survival of planted seedlings was expected. A lower survival rate of 35 percent was expected for low rainfall years. In addition to these differing weather conditions, this regime included a re-planting scenario.

Alternative 2: Herbicides only—This model employed site preparation consisting of spraying herbicides with seedlings hand-planted directly into old fields. During good weather conditions with adequate rainfall, 85 percent survival of planted seedlings was expected. A lower survival rate of 70 percent was expected for low rainfall years.

DATA

Forest land managers have recognized the importance of competition control in pine survival and growth. A regional study established that grass and herbaceous broadleaf plants are the most serious competitors during the first 5 years of pine growth and development. Since oak planting has not been studied to any comparable extent and expectations for oak seedling growth are less than for pine, the impact of competition on survival has received far less attention.

Three primary factors determining initial survival of planted oak seedlings are planting stock quality, planting job quality, and competition control. Obviously, control for the latter will be of little benefit if the two former criteria are the cause of mortality. However, seedling quality in terms of size and condition may be specified during the ordering process, and supervision can typically ensure an acceptable planting job. Given that good seedlings have been planted properly, the control of competing vegetation can have striking effects on first year survival. In a study involving six oak species (*Quercus* spp.) and green ash (*Fraxinus pennsylvanica* Marsh.), Ezell and Catchot (1997) found survival was increased 15-20 percent for all species by applications of herbicide prior to bud break. The research was completed during a growing season with normal precipitation for the area, and survival in the treated areas averaged 85-90 percent, depending on the species. An examination of the effect of competition control on oak seedlings during droughty years found survival in treated areas remained in the 80-90 percent range for Nuttall (*Q. nuttallii* Palmer) and

cherrybark oak (*Q. pagoda* Raf.) while survival in the untreated areas ranged from 0 to 43 percent (Ezell 2000). The impact of competition was enhanced by a severe drought at the research site during 1998 and 1999.

Yield Information

Given the lack of growth and yield information for oak plantations in the mid-South, this study used observational information for mixed oak stands on abandoned agricultural lands. Our approach was similar to the one used by Ezell and Bullard (1997). Although our analysis was concerned with returns from oak plantations, the yield estimates for mixed oak natural stands served as a basis for utilizing our estimated returns as a worst case scenario. Therefore, land expectation values presented in this paper were considered conservative estimates for the different types of vegetation controls implemented to improve seedling survival. We feel that this assumption was appropriate because plantations were assumed to be managed in a more intensive manner resulting in greater growth and yield.

Our models assumed that on a per acre basis, oaks will start to accumulate 350 board feet Doyle per year at age 25, and final harvest will be at age 50, leading to the accumulation of 8,050 board feet of volume per acre. In addition, we assumed one thinning at age 35 will yield 5 cords and 2,000 board feet Doyle per acre, and that 10 cords per acre will be cut during final harvest along with the 8,050 board feet per acre of sawtimber. A lack of empirical growth and yield data prohibited the use of either maximum mean annual increment or financial criteria to determine the optimal rotation age.

Cost Information

Cost information used in this study was collected through published and unpublished sources. In this analysis, a 6 percent real discount rate was used. Average costs per acre per activity in 2002 are reported in table 1.

Price and Revenue Information

The price data used to compute harvest values were taken from Timber Mart South for 2002. In addition, it was assumed that landowners would be able to lease their land for fee hunting purposes at an average of $5.50 per acre per year. This is consistent with Jones and others (2001). Table 2 summarizes this information.

RESULTS

To compare the returns for competition control using alternative management regimes, land expectation value was calculated for each regime given the before-stated assumptions. Given the growth and yield assumptions, these results should be viewed as conservative estimates for the different management practices during both good and bad rainfall years. Table 3 presents after-tax results for the base case and alternative management regimes. For the base case during good rainfall years, expected stand establishment was better than in bad rainfall years, despite no control for competing competition. This results in a $165.21 difference in after-tax LEV between good and bad rainfall years. The after-tax LEV difference between disking and herbicide use and the no site preparation was $8.35 and $117.17 for good rainfall years and $11.17 and $193.81 for bad rainfall years.

Table 1—Average cost per acre by activity for Mississippi in 2002

Activity	$ per acre
Herbicide application	35
Disking	20
Seedlings[a]	109
Hand planting	47
Land use tax[b]	2
Annual management fees	2

[a] Seedling price is $0.25 per seedling and 435 seedlings planted per acre.
[b] Average per acre land-use tax for forest land in the Mid-South is approximately $2.

Table 2—Price and revenue information for standing timber and fee hunting in 2002

Species	Prices
Oak sawtimber	$302.00 per MBF Doyle
Hardwood pulpwood	$13.74 per cord
Hunting leases	$5.50 per acre per year

Table 3—After-tax LEV per acre results for alternative management regimes

	No site preparation	Disking only	Herbicides only
		dollars	
Good rainfall year	185.45	193.79	302.62
Bad rainfall year	20.24	31.41	214.05

DISCUSSION

In general, greater vegetation control had an impact on an after-tax land expectation values for the studied management practices. However, there are many factors that may affect the results of this study. In this discussion, we address the importance of incentive programs and prices.

An important issue affecting hardwood plantation returns are federal and state incentive programs and state tax credits. State incentive programs, such as the Forest Resource Development Program in Mississippi, provide financial assistance and technical support to landowners. Unfortunately, given high demand for these monetary resources, not all programs can offer 50 percent cost share for site establishment. If actual cost shares are less than those assumed for this study, then hardwood investment

returns would be lower when considering either before- or after-tax calculations. In addition, high demand forces landowners to add their names to a waiting list, which in no way guarantees that funds will be awarded. However, landowners who live in a state with a reforestation tax credit have another alternative for receiving financial assistance. For instance, in Mississippi, the state legislature recently enacted a law providing private landowners a $10,000 life time tax credit for reforestation. This credit neither prevents a landowner from claiming the federal investment tax credit nor prevents amortization of reforestation expenses for 8 tax years. Programs like this can greatly improve the investment return of hardwood plantations.

Last is the role that prices and interest rates have on an investor's decision to invest in oak plantations. LEV estimates are very sensitive to changes in prices and discount rates. Higher discount rates lower LEV estimates while lower rates increase these estimates. The after-tax discount rate used in this analysis is lower than the before-tax rate, which increases the LEV estimates. The discount rate used by the investor will greatly influence the decision to establish an oak stand. In addition, many investors assume a 1 to 2 percent real appreciation of stumpage prices over the rotation. This will improve LEV estimates making the oak plantation investment more attractive.

CONCLUSIONS

In summary, the goal of this study was to examine the role competition control plays in seedling survival and whether or not it affected investment returns for oak plantations. The analytical approach utilized after-tax land expectation value estimates to conduct a comparative analysis of different management regimes. The management regimes incorporated different competition control procedures that yielded different seedling survival during good and bad rainfall years. The results suggested that to control competition and maximize returns, management regimes should spray herbicides only, despite good or bad rainfall years after initial stand establishment.

ACKNOWLEDGMENTS

Approved for publication as Journal Article No. FO229 of the Forest and Wildlife Research Center, Mississippi State University. Our thanks are given to Drs. Andrew J. Londo and Keith L. Belli for constructive criticisms.

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MECHANICAL DAMAGE INCURRED BY UNDERPLANTED NORTHERN RED OAK FOLLOWING SIX OVERSTORY TREATMENTS: FIRST-YEAR RESULTS

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Abstract—Regenerating oak, on recently harvested sites, continues to be a silvicultural challenge in the Central Hardwood Region. Enrichment planting can increase oak regeneration potential and success during the early stages of cohort development. In April of 2002, a replicated oak silviculture study using artificial regeneration was established near Oak Ridge, TN. Nursery-grown, 1-0, bareroot northern red oak (*Quercus rubra* L.) seedlings were underplanted prior to timber harvesting. Six overstory treatments, no cut (control), silvicultural clearcut, commercial clearcut, and 50, 25, and 12.5 percent basal area (BA) retentions, were implemented after planting, with each being replicated 3 times for a total of 18 overstory treatment units. Seedlings were assigned to harvest damage classes in order to assess the effect of operational damage on their growth and competitiveness. There were no significant differences in mortality between the cutting treatments, but mortality as high as 83 percent (12.5 percent BA retention) suggested substantial losses due to harvesting. Twig damage differed significantly between cutting treatments ($P < 0.05$). Pre-harvest underplanting in mature stands similar to those treated in this study resulted in high seedling mortality and varying levels of damage, depending on harvest intensity.

INTRODUCTION

Regenerating oak-dominated (*Quercus* spp.) stands continues to be a difficult endeavor throughout the Eastern deciduous forest. This problem is directly related to the paucity of oak regeneration in the subcanopy of oak-dominated stands. Oak regeneration success is strongly linked to the presence of oak in the advance regeneration pool (Larsen and Johnson 1998). The absence of numerous, large oak advance regeneration in oak-dominated stands prior to canopy disturbance can lead to the replacement of oaks by faster growing species and, also, more shade-tolerant species (Johnson 1993, Loftis 1990, Sander 1972). The issue of oak replacement is more acute on productive sites, since competition is more aggressive (Loftis 1983, Rogers and Johnson 1998). Furthermore, the inadequacy of oak seedling establishment after disturbance exacerbates the oak regeneration problem, since there is little contribution to early stand development from oak seedlings that germinate after disturbance (Loftis 1990, McGee and Hooper 1970).

Large oak advance regeneration is necessary because small seedlings do not respond quickly to growing space release, which allows faster growing competitors to overtop and suppress small oak regeneration (Loftis 1990, Sander 1972). The development of large oak advance regeneration can take a decade or longer (Sander and others 1983). Many landowners are not willing to invest in the time and expense required to develop adequate oak advance regeneration before final harvest.

An alternative to natural oak regeneration is artificial regeneration. Nursery-grown seedlings can supplement natural oak regeneration and cut down on the time required to develop adequate advance regeneration (Wendel 1980). The decision to plant either before or after harvesting must involve the advantages and disadvantages of both techniques. Planting after harvest can subject seedlings to intense temperature and moisture fluctuations, which can stress seedlings as they adjust to field conditions, but precludes harvesting damage. Underplanting prior to harvest will allow seedlings to adjust to field conditions ameliorated by a canopy, yet harvest damage to seedlings is inevitable (Dey and Parker 1997). Operationally, planting after harvest can be more difficult than planting before harvest because of planting in and around logging residues. Knowing the impacts of harvest intensity on underplanted seedlings can help foresters calculate expected losses in order to implement a successful planting operation. The objective of this study is to evaluate the effects of timber harvesting on physical damage to underplanted seedlings.

STUDY SITE

In fall 2001, a 75-acre harvest and oak regeneration study was initiated at the University of Tennessee's Forestry Experiment Station in Oak Ridge, TN. The Oak Ridge Experiment Station is located within the Ridge & Valley Physiographic Province within the Central Hardwood Region. The study site was a mixed hardwood assemblage composed primarily of upland oaks, yellow poplar (*Liriodendron tulipifera* L.), and various shade-tolerant hardwoods, such as red and sugar maple (*Acer rubrum* L. and *A. saccharum* Marsh., respectively).

METHODS

High quality northern red oak (*Quercus rubra* L.) seedlings were outplanted to evaluate the efficacy of preharvest enrichment planting and overstory removal in regenerating oak. Seedlings were provided by the University of Tennessee's Tree Improvement Program. The seedling stock was graded using an ocular system based on size and condition. Seedlings were separated into three grades: premium, good, and potential cull. Only premium and good seedlings were outplanted.

The experimental design is a randomized block design (RBD). Block differences were determined to be significant

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

using pre-harvest stand basal area data. A total of three replicate blocks were used and each block was divided into six overstory treatment units.

Six overstory treatments were implemented during the late spring and early summer of 2002. The overstory treatments are: (1) silvicultural clearcut (SCC), (2) commercial clearcut (CCC), (3) 12.5 percent basal area (BA) retention, (4) 25 percent BA retention, (5) 50 percent BA retention, and (6) no cut (control). The basal area retention units were marked in order to create a uniformly distributed residual stand. The treatments were assigned at random within 3 complete blocks for a total of 18 experimental units of approximately 4 acres each.

Within each treatment block, 60 1-0 bareroot seedlings were planted prior to the harvesting sequence. Both shovels and an auger were used in the planting operation. Seedlings were planted on a 20- by 20-foot spacing to facilitate their relocation for measurement. The seedlings were concentrated toward the center of each block to avoid edge effects.

Outplanted seedlings were examined following the harvest operation to determine the type and magnitude of damages they sustained. A seedling damage classification system was developed to provide a framework for characterizing seedling condition, identifying the forms of damage, and quantifying mechanical damage associated with the harvest treatments. Seedling survival was determined for the 2002 growing season only. Therefore, any seedling not showing vital signs (i.e. bud break, sprouting) was assumed dead. Damage to live seedlings was separated into stem and twig categories for analysis. In the control units, seedling stem dieback was viewed as stem damage, while twig dieback and herbivory were recorded as twig damage.

All statistical analysis was conducted using SAS software (SAS Institute Inc. 2001). Mixed model analysis of variance (MMAOV) was used to determine the effects of the overstory removal treatments in relation to seedling survival and damage. For survival, this was determined by testing whether mortality varied between treatment units. Mortality in this case was the summation of top-killed, killed (uprooted or without vital signs), and missing (seedling not found, therefore, status unconfirmed) seedlings minus the number of sprouting top-killed seedlings. The mortality figure was converted into a percent mortality for each treatment unit. Analysis of damages incurred by living seedlings was conducted to test for treatment effects. Stem and twig damage values represent the number of seedlings in each treatment unit displaying those damages. Associations between mortality, stem damage, and twig damage were evaluated through correlation analysis.

Tukey's HSD was performed in order to identify which means differed when MMAOV found significant treatment effects. Contrasts were used to determine if specific combinations of treatments differed significantly. The patterns of response (linear, quadratic, etc.) for percent mortality, twig damage, and stem damage across the treatment levels were explored using orthogonal polynomial contrasts.

RESULTS

Seedling Survival

Treatment effects on seedling mortality were significant at the 5 percent level (table 1). Tukey's mean separation indicated that the significant differences exist between the 12.5 percent BA retention (83 percent mortality) and the control (42 percent mortality). However, this result occured only when the control units were included in the analysis. Mean separation confirmed this result by grouping all overstory removal treatments together. Therefore, there were no significant differences in seedling survival between the cuttings.

Contrast analysis of the combined effects of complete removal treatments (silvicultural and commercial clearcuts) against partial cutting treatments (12.5, 25, and 50 percent BA retentions) on seedling mortality was not significant at the 5 percent level. This result is similar to the findings of Tukey's mean separation. Orthogonal polynomial contrasts identified that seedling mortality changed linearly across the harvest intensity gradient ($P < 0.05$), while all other patterns (i.e., quadratic and cubic) were not significant.

Seedling Damage

MMAOV indicated that the harvest treatments had significant effects on twig damage to live seedlings at the 5 percent level but not stem damage (table 1). Tukey's mean separation for twig damage means indicated that there were significant differences between the cutting treatments. Specifically, the 50 percent BA retention mean (27 seedlings damaged) was not grouped together with the commercial clearcut or the 12.5 percent BA retention means (both with 9 seedlings damaged) (table 1).

Table 1—Treatment and control means for a harvest and oak regeneration study at the Oak Ridge Forestry Experiment Station, TN

	Overstory treatment levels					
Seedling status	Control	50	25	12.5	CCC	SCC
Percent mortality	42b	57ab	75ab	83a	78ab	76ab
Twig damage	10ab	27a	16ab	9b	9b	10ab
Stem damage	8a	24a	12a	8a	12a	13a

CCC = commercial clearcut; SCC = silvicultural clearcut.
Means are percent mortality, number of seedlings with twig damage, and number of seedlings with stem damage of underplanted northern red oak (*Quercus rubra* L.) for 2002. Means followed by the same letter are not statistically different according to Tukey's HSD at $\alpha = 0.05$.

Since treatment effects on stem damage were not found to be statistically significant, contrast analysis was only performed for twig damage means. Two combinations of treatment means for twig damage were explored for significant differences. The same contrast used in the seedling mortality analysis (clearcuts vs. retentions) was used for twig damage. Contrast analysis found the two combinations to be significantly different ($P < 0.05$). The average of the SCC, CCC, and 12.5 BA percent retention means were compared to the average of the 25 and 50 BA percent retention means due to Tukey's mean grouping (table 1). Contrast analysis found the two groupings to be significantly different ($P < 0.05$). The orthogonal polynomial contrast for twig damage showed a significant quadratic and cubic pattern of change across the harvest intensity gradient ($\alpha = 0.05$). The quadratic pattern of twig damage emerged across the cutting treatments and decreased as harvest intensity increases. The cubic pattern arises at the low end of the removal intensity gradient where there was a sharp increase in twig damage moving from the controls to the 50 percent BA retention units.

Seedling Mortality and Damage

Correlation analysis for both mortality and damage factors were conducted with a 3 by 3 matrix of percent mortality, stem damage, and twig damage (table 2). The analysis indicated significant associations between both percent mortality and twig damage with stem damage ($P < 0.05$). The correlations between both percent mortality, and twig damage with stem damage were –0.48 and 0.79, respectively.

DISCUSSION

Seedling survival for the 2002 growing season was linked to harvesting. Although mean separation was unable to find significant differences between the cutting units, the analysis did find that mortality in cutting units was significantly greater than in control units (table 1). Although control units were undisturbed by logging, dieback mortality of planted seedlings did occur in the control units. The seedling's intolerance to overhead shade and water stress associated with the 2002 summer dry spell probably contributed to this mortality.

Although there were no significant differences between the cutting units, seedling mortality was observed to be greatest in the 12.5 percent BA retention, CCC, and SCC units.

Table 2—Correlations of three response variables measured in a harvest and oak regeneration study at the Oak Ridge Forestry Experiment Station, TN in 2002

	Percent mortality	Twig damage	Stem damage
Percent mortality	1	-0.43 P > 0.05	-0.48* P < 0.05
Twig damage		1	0.8* P < 0.0001
Stem damage			1

Matrix with percent mortality, twig damage, and stem damage showing correlation coefficients and *P*-values. Correlation coefficients followed by an asterisk are statistically significant at $\alpha = 0.05$.

High mortality in these units is likely the result of a combination of factors. One obvious explanation is the high cutting intensity, which led to increased felling and skidding. With increased felling comes heavy damage to midstory and understory vegetation. The more widely spaced trees in the residual stand were less restrictive to skidding. This allowed operators to skid timber freely with little worry of damaging residual trees. The lower mortality in the 25 percent and 50 percent BA retention units indicated that skidding might be more concentrated on areas where damage to residual trees was less likely. Furthermore, the openness of the intensely harvested units may have stressed seedlings and caused mortality through increased exposure to solar radiation and desiccating winds.

A linear pattern of mortality across the overstory removal treatments was found, indicating that seedling mortality increased linearly along the overstory removal gradient.

Twig damage was the only type of damage that was significantly impacted by overstory removal (table 1). The 50 percent BA retention treatment had the highest level of twig damage while the commercial clearcut and 12.5 percent BA retention units had the least. This is practically the inverse of the mortality trend. There was less severe destruction of understory vegetation in the 50 percent units, since fewer trees were harvested and the higher retention restricted skidders from meandering across these units. Instead, skidding was concentrated in areas where damage to residual trees could be avoided. The partial cutting in the 50 percent retention units created more low-level damage, such as twig breakage, compared to the intense removal treatments (clearcuts and 12.5 percent retention). The primary reason for less twig damage in the SCC, CCC, and 12.5 percent retention units was due to higher mortality, which left few intact seedlings that could sustain twig damage. Although it is likely that a substantial number of seedlings categorized as dead in the SCC, CCC, and 12.5 percent units sustained twig damage, mortality precluded the identification of twig damage to seedlings in this study.

Twig damage in the partial cutting units versus complete cutting units indicated that the two treatment combinations were significantly different from each other. This result showed that one can expect partial cutting to have a different impact on seedling damage compared to complete cutting. The groupings of the twig damage means showed a more complex pattern in relation to partial cutting and complete cutting. The MMAOV and mean separation of twig damage indicated the 50 and 12.5 percent BA retention units were significantly different, which is inconsistent with the results of the partial vs. complete cut contrast. Instead, a contrast of the complete cuts + 12.5 percent retention and the 25 and 50 percent retentions was performed and indicated a strong significant difference ($P < 0.002$). This result implied that one can expect that a combination of intense partial and complete cutting will cause significantly different levels of damage to underplanted seedlings compared to moderate partial cutting.

The response in twig damage across the overstory removal gradient followed both quadratic and cubic patterns in this

study. The quadratic pattern occurred across the cutting treatments (table 1). Specifically, twig damage decreased exponentially as harvest intensity increased producing a concave pattern. This translated into a rapid decrease in twig damage moving from the 50 percent retention to the 12.5 percent retention and a leveling out across the clear-cut units. The cubic pattern appeared because of the influence of the control units. At the low end of the removal gradient, there was a dramatic increase in twig damage moving between the controls and 50 percent units followed by a noticeable decrease continuing on to the 25 percent units. This peak represented a cubic change in twig damage across this section of the overstory treatment gradient.

The two significant correlations between seedling mortality and stem damage, r = -0.48, and twig damage and stem damage, r = 0.79, recapitulated the relationship between harvesting and damage to underplanted seedlings observed in this study (table 2). A moderate negative association between seedling mortality and stem damage translated to an increase in mortality being accompanied by a decrease in stem damage. Although not statistically significant, higher mortality was experienced in units with greater harvesting intensity, which produced greater destruction of underplanted seedlings. Therefore, seedlings were more prone to total stem destruction following intense overstory removal compared to low-level damage, such as stem damage. A strong positive correlation between twig damage and stem damage suggested the two covary. Seedling damage was greatest for the moderately intense cutting treatments where low-level damage predominated. Specifically, an increase in twig damage was accompanied by an increase in stem damage and the two changes were directly linked. In other words, seedlings that experienced twig damage also incurred stem damage.

CONCLUSIONS

First year results indicate that underplanting in conjunction with harvesting can substantially impact seedling survival. With as much as 83 percent mortality (12.5 percent retention) and no statistical differences in seedling mortality between the cutting treatments, a significant loss of underplanted seedlings can be expected when harvesting in stands similar to those treated in this study. However, since these are one year results, the seedling mortality figures may be overestimates due to potential sprouting of seedlings formerly classified as dead (end of the 2002 growing season) during the 2003 growing season.

The assessment of twig damage showed that moderate basal area removal generated substantial damage with the 50 percent BA retention resulting in twig damage to nearly half (mean = 27) of the seedlings in those units. Furthermore, it is likely that twig damage was severe in the heavily cut units but was masked by high mortality. The study area consisted primarily of mature forest, which may have exaggerated the amount of damage incurred by the seedling stock. An alternative to underplanting in mature stands would be to plant after harvest and avoid any negative direct impacts related to harvesting large timber. Post-harvest planting is, however, more logistically difficult, because of logging residue.

Harvesting effects on seedling survival and damage may have been exacerbated by the short time interval between the planting operation and timber harvesting. The seedlings were subjected to multiple episodes of handling before outplanting and were likely in a state of shock from being lifted from a favorable nursery setting and placed in the field. The sudden alteration of the microenvironment brought about by harvesting may have overwhelmed many of the seedlings, since they were acclimating to field conditions when harvesting took place and also had little time to put down roots to resist uprooting and facilitate sprouting. This point suggests that underplanted seedlings may require a few growing seasons of adjustment before overstory removal.

ACKNOWLEDGMENTS

We thank the University of Tennessee's Department of Forestry, Wildlife, and Fisheries for financial support, Dr. David S. Buckley for reviewing this paper, and the University of Tennessee's Tree Improvement Program and Forestry Experiment Station for assistance in several phases of this project.

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NORTHERN RED OAK FROM ACORNS TO ACORNS IN 8 YEARS OR LESS

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Abstract—The intrinsic factors affecting acorn production in oak trees need further study. Common knowledge holds that an oak requires a minimum number of years to begin flowering, with 30 to 50 most frequently reported. Recently, the Institute of Tree Root Biology has been studying the development of northern red oak (*Quercus rubra* L.) in the nursery and in outplanting situations. The goals are (1) refining a silvicultural system for oak regeneration on high-quality mesic sites, and (2) pinpointing nursery seedlings most likely to develop into competitive forest trees. Over the course of these studies, we have noted precocious acorn production from these seedlings deemed most competitive in the nursery. Therefore, we speculate that the minimal physiological maturity necessary for flowering to initiate may be more closely related to carbohydrate production than to age.

INTRODUCTION

Northern red oak (*Quercus rubra* L.) (NRO) is the premier multiple-use forest species throughout its range in the Eastern United States. It reaches its maximum productivity for mast and timber on high-quality mesic sites. Throughout NRO's range, its acorns are as highly prized as its timber because of the important role mast crops play in supporting a diverse, healthy wildlife population. However, the environmental and edaphic factors affecting acorn production, and their interactions with oak biology, are poorly understood (Cecich 1993).

Early reports correlated initiation of acorn production primarily to tree age: 40 to 50 years was considered to be the average time needed for a NRO to begin mast production (Busgen and Munch 1929). More recent studies in the United States have reported 20 to 40 years as the age of acorn crop initiation (Beck 1993, Cecich 1993, U.S. Department of Agriculture 1974). However, individual oaks exhibiting exceptional early growth may produce acorns much sooner.

Beck (1993) reported the extrinsic and intrinsic factors influencing acorn production and concluded that the extrinsic factors, such as weather, insects, and wildlife, while more commonly studied, were secondary in importance to the roles intrinsic factors, such as genetics and physiological condition, play in the initiation of acorn production. Early identification of those individuals predisposed to precocious acorn production would be of considerable value to silviculturists and wildlife biologists, who could then keep those crowns free of competition to enhance consistent mast production (Cecich 1993).

The Institute of Tree Root Biology (ITRB) and the Georgia Forestry Commission (GFC) have developed nursery protocols for evaluating competitive potential of individual oak seedlings when lifted from the nursery bed as 1-0 stock. Several years ago, we established and maintained small plantings (1 to 3 ha) of these graded seedlings from over 100 open-pollinated half-sib mother trees under various management intensities to evaluate field performance. These early studies were not implemented specifically to elucidate factors affecting mast production but rather to develop technology for establishing young stands on high-quality mesic sites. Early acorn production was an unexpected bonus with significant practical as well as biological implications.

The purpose of this report is to describe what has been observed about early acorn production when NRO seedlings are grown following the ITRB nursery protocol and evaluated on specific morphological characteristics prior to outplanting.

METHODS

Acorns

Acorns for the three studies were collected from specific NRO mother trees from either the USDA Forest Service's Watuga Seed Orchard in eastern Tennessee, from individuals in the Chattahoochee National Forests in Georgia, or from the National Forests in North Carolina. The acorns were floated in water, and those that sank were presumed sound (Olson 1974) and placed in cold storage (4 to 6 °C) until sown. Sowing took place in early to mid-December either at the GFC Flint River Nursery near Montezuma, GA, or the ITRB Whitehall Experimental Nursery, Athens, GA. Nursery management practices at both locations follow the same protocol as described in the next section.

Bed densities are selected to achieve a seedling density of 54 to 57/m^2. Acorns from specific mother trees are sown continuously within a bed, with a 2-m void between individual half-sib seedlots. Well-decomposed sawdust was then applied to all beds to a depth of 2 to 3 cm.

Nursery Protocol

Before sowing, nursery soils were sampled for nutrient status and then adjusted to the Flint River soil baseline fertility level for calcium, potassium, phosphorus, magnesium,

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

copper, zinc, and boron: 600, 130, 100, 75, 0.3 to 3, 3 to 8, and 0.4 to 1.2 parts per million, respectively (Kormanik and others 1994). Nitrogen was applied as NH_4NO_3 at 10- to 14-day intervals throughout the growing season, beginning about the time of first flush in mid-May until early September. The rates were gradually increased as the seedlings developed and were able to more efficiently absorb the top dressing. The first two applications were at approximately 22 kg/ha, the 3rd at 56 kg/ha, the 4th through the 10th at 168 kg/ha, and the final two at 116 kg/ha. Irrigation was provided throughout the growing season to supplement rainfall when < 2.5 cm/week occurred. Irrigation continued as needed until the leaf abscission layer developed following several frosts in late November.

Seedling Grading

All seedlings were root pruned at approximately 30-cm depth prior to lifting in mid-February. The seedlings were lifted, graded, and their first-order lateral roots (FOLR) were cut to 15 cm length. The seedlings used in the Flint River Seed Orchard had minimum FOLR numbers of 15 and the minimum height (HGT) and root-collar diameter (RCD) at 1.25 m and 15 mm, respectively. The planting at the Beech Creek Seed Orchard located in North Carolina and the Blairsville Ranger District in north Georgia were both considered regular outplantings, and the minimum FOLR number of these seedlings was six and the minimum HGT and RCD were 0.70 m and 8 mm, respectively. These seedlings represented the top 40 to 60 percent of the progeny.

Outplanting

Seedlings were produced at the ITRB Nursery, and 5 of the best individuals were selected from each of the 14 mother trees for long-term developmental observation. A single individual from each mother tree was randomly outplanted at the Flint River Seed Orchard in each of five blocks at 4.5- by 9.1-m spacing.

The Flint River Seed Orchard soil fertility was tested biennially and maintained at levels comparable to those in the nursery beds. Nitrogen was applied at rates equivalent to 350 kg/ha of product during years 2, 3, and 4. Subsequently, fertilizer was applied only to correct any departures from soil protocol. Irrigation ceased after top dressing with NH_4NO_3. Progeny grown at the Flint River Nursery from 10 mother trees were outplanted in 3 replicates in a traditional progeny trial design, with 5 tree groups for each half-sib progeny at 4.5- by 9.1-m spacing. No fertilizers or irrigation were used at this orchard.

The Blairsville site involved 25 mother trees in 10 replicates also in a traditional progeny trial layout with 5 tree groupings, but at 3.1- by 3.6-m spacing. No fertilizer or irrigation was used at this site.

RESULTS AND DISCUSSION

It must be emphasized that the three plantings discussed here must be considered as individual case studies, and none of them was designed to study early acorn production *per se*. They have little in common except for being grown in the nurseries under an identical management protocol. Even the minimum acceptable measurements for FOLR, HGT, and RCD differed for each study. The Flint River Seed Orchard planting included selections from the top 5 percent of the progeny from selected mother trees. Those planted at the Beech Creek locations and Blairsville would more realistically represent those from the top 40 to 60 percent of progeny. Both the Beech Creek and Blairsville plantings were on good-quality mesic sites, and we wanted to determine how our selected trees would develop in the absence of irrigation and supplemental fertilization. Seedlings were anticipated to be competitive after outplanting, but those from the two latter plantings were not as uniform in morphological characteristics as those planted at the Flint River Seed Orchard.

The primary management tool during this establishment period was competition control, either by chemical or mechanical means. When the seedlings were outplanted, we expected that thinning would be required around age 10 to 15 to maintain thrifty crowns. Also, we planned to evaluate whether the stands needed other management treatments to enhance their acorn production potential. This approach in delayed anticipation of acorn production reflected the commonly held concept that initiation of acorn production was more a function of age than of individual tree vigor (Beck 1993, Busgen and Munch 1929, Cecich 1993, U.S. Department of Agriculture 1974). However, these reports did indicate acorn production as early as age 10 occasionally occurred on the most vigorous trees. On the other hand, Zimmerman and Brown (1971) suggested that it was crown size and vigor, rather than age *per se*, that may be involved in early initiation of seed production in trees. The three case studies reported here concur with the view on early acorn production by Zimmerman and Brown (1971). This information has significant ramifications for multiple-use management.

Flint River Seed Orchard

This outplanting was established in 1992. The nursery study was designed to determine the heritability of FOLR of this species, and no subsequent field testing was anticipated at the time of the study's initiation (Kormanik and others 1997, 1999). However, the GFC outplanted the best individuals at their newly developed hardwood seed orchard, the Flint River Nursery. The precise locations of the individual mother trees were unknown; only the general areas of collection in north Georgia and western North Carolina were available. Thus, 5 seedlings from each of the 14 mother trees were selected, but progeny identity within blocks was not maintained.

Midway through the fourth growing season, a small number of acornets were observed on individual trees in all five blocks. The acornet-bearing trees were marked, but no effort was made to evaluate the entire planting. Periodically, the trees were observed to determine if acornet abortion occurred during the intense heat of south Georgia summers. A few individuals retained a portion of their acornets, which matured during the fifth growing season.

Acorns were produced sporadically from the sixth to the ninth growing seasons, but characteristically, a significant percentage aborted during either the season of initial acornet production or during maturation. High summer

temperatures accompanied by an extensive drought characterized all these years. In spite of the extended drought, a large commercial-size crop was produced during the 10th season (2002). Of the surviving 61 trees, 5 were classified as heavy producers, 9 as medium producers, 26 as light producers, and 21 as nonproducers. The average HGT, diameter at breast height, and mean acorn-bearing status for each of the five blocks are shown in table 1. Since the fifth growing season, 41 of the surviving 61 trees have produced acorns at least one time.

Beech Creek Seed Orchard

Beech Creek Seed Orchard, as well as the Blairsville planting, were established in 1995 and have never been fertilized or irrigated. The heavy fescue cover at the Beech Creek location was treated with herbicide to maintain a 2-m-wide grass-free strip along each row of trees. No measurements were made on the young trees. The trees have remained free of intraspecies competition because of the wide spacing and mortality from animal damage. Survival was very good, but excessive deer (*Cervidae* spp.) browsing adversely affected two progeny groups. None of the family 482 progeny recovered height growth from browsing, and only 45 percent of family 427 progeny survived (table 2). The progeny from one mother tree (482 in this case) was especially susceptible to deer damage and was unable to recover from repeated browsing, severe drought, and high summer temperatures.

Table 1—Heights, diameters, survival, and estimates of acorn production for the 10th-year northern red oak at the Georgia Forestry Commission, Flint River Seed Orchard

Block	Height	D.b.h.	Survival	Acorn status[a]
	m	*mm*	*percent*	
1	6.2	124	86	1.3
2	6.8	133	93	1.3
3	6.8	142	79	0.5
4	7.0	129	93	0.8
5	6.2	119	86	0.9

[a] Acorn production of the 61 surviving trees was assessed on a relative, subjective basis as follows: 0 = no acorn production (1 tree); 1 = light production (26 trees); 2 = moderate production (9 trees); and 3 = heavy acorn production (5 trees).

Table 2—Height, diameter, and survival of the eighth-year northern red oak outplanting at the Beech Creek Seed Orchard

Family	Height	D.b.h.	Survival
	m	*mm*	*percent*
419	4.4	75.4	100
422	3.7	47.4	60
427	3.6	47.8	45
429	3.4	43.1	87
434	3.9	57.6	80
442	4.0	60.3	80
450	3.8	54.8	80
457	4.2	65.8	100
472	4.2	60.2	87
473	3.6	54.7	60
482	—	—	0

Until the end of the fifth growing season, the planting had not been surveyed for acorn development. In October 2000, we observed acorn production on approximately 10 percent of the trees but made no permanent record. We observed additional acorn production on other individuals in 2001 and again in 2002 when measuring the surviving trees. To obtain acorn production in this case, even in limited numbers, is quite impressive because of the record-breaking drought in progress for at least 6 of the 7 years since the trees were outplanted. Based on the Flint River Seed Orchard success, we will begin fertilizing Beech Creek at comparable rates to determine if acorn production can be increased to similar levels.

Blairsville Outplanting

The Blairsville outplanting, established in 1995, was an early effort to determine whether NRO could be artificially re-established on high-quality mesic sites in the Appalachian Mountain region of the Southeastern United States. Initially, interspecific competition was considerable, as thousands of germinated and stump-sprouted yellow-poplar (*Liriodendron tulipifera* L.) blanketed the study site. The competition was controlled both mechanically and with herbicide during the second and third growing seasons. The NRO oak responded to this release, and crown closure occurred by age 4. Since the third growing season, grape (*Vitis* spp.) vines have been a nagging problem along the outside perimeter of the planting. Vole (*Cricetadae* spp.) damage accounted for the vast majority of seedling mortality during the first 2 years in the field.

The first acorn production noted was at the end of the seventh growing season (2001), but crown closure prevented assessment of acorn production while the crowns were in full leaf. Acorns were observed on the ground below five or six trees in December 2001, but no intensive survey of the trees was made. The entire planting was surveyed for acornet development prior to bud break in spring 2002. Progeny from 16 of the 25 families had individuals with acornets (table 3). The poor performance of family 482 progeny observed at the Beech Creek Orchard did not occur at this location. Deer damage was minimal on this site, and maturing acorns were periodically observed throughout the summer. An extensive hot spell accompanied by drought resulted in some acorn abortion in early August 2002. All individuals we observed with acornets in the spring eventually produced some mature acorns in the fall. However, because of severe crown competition throughout the 2002 growing season, it was not practical to make assessments of acorn counts on an individual tree basis.

In early September we cleared vegetation beneath the trees in preparation for acorn collection. Unfortunately, when we revisited the site 2 weeks later to determine status of acorn drop, we found few acorns remained. Squirrels (*Sciuridae* spp.) had essentially consumed all the acorns—even the immature ones. Checking various oak species in the adjacent natural stand revealed that few acorns were present, and the 2002 season was to be a very poor mast year.

Table 3—Height, diameter, volume, and survival of the eighth-year northern red oak outplanting at Blairsville

Family	Height	D.b.h.	Volume	Survival
	m	*mm*	*cm³*	*percent*
435[a]	3.7	30	5069	72
439[a]	3.6	31	4822	86
442[a]	3.9	35	6401	82
443[a]	3.8	32	4691	78
448[a]	3.2	24	2825	72
473[a]	4.0	38	7822	56
479[a]	3.9	36	7651	74
482[a]	4.2	39	8469	84
419[a]	4.0	37	6902	86
421[a]	3.9	36	7031	72
423[a]	3.5	30	4533	74
441[a]	3.8	34	6787	78
450[a]	3.6	32	5551	68
459[a]	3.0	25	3388	68
468[a]	3.0	24	2468	84
483[a]	3.7	35	7930	72
438	4.0	34	5675	76
420	3.2	26	2939	68
437	3.5	31	4378	80
451	3.9	33	5785	82
469	3.0	24	2391	82
474	4.0	36	6976	70
480	3.2	26	3208	76
481	3.5	29	4615	84
484	3.1	27	3539	76

[a] Produced acorns.

The stand was thinned in December 2002 to permit greater crown expansion. No individuals with second-year maturing acorns or with acornets were removed in this thinning. Management of this outplanting will be directed toward acorn production for wildlife as well as a collection site to obtain acorns for nursery production.

CONCLUSIONS

In the past scientists may have overemphasized the effects of tree age on initiation of acorn production. After observing natural forest stands, scientists may correlate acorn production too closely with years after outplanting. Our observations clearly indicate that crown vigor, combined with genetic potential, may be an overriding factor in early acorn production. The potential of individuals to make accelerated growth can be predicted based upon their competitive behavior under specific nursery conditions. The genetic involvement in precocious acorn production is apparent, since some individuals make exceptional growth and produce acorns annually, but others of comparable vigor have not yet produced acorns. To obtain early acorn production even with the best quality seedlings, interspecific competition must be reduced so that the crowns are exposed to full sunlight during early development. It is unlikely that overtopped seedlings will develop the root systems necessary to allow initiation and sustenance of vigorous crowns that are essential to early acorn production.

Seedlings from the top 5 to 10 percent of a given crop, such as those at Flint River Seed Orchard, are very uniform and may contain the most potential acorn producers. However, even those from the top 40 to 60 percent of the crop, such as those at Blairsville and Beech Creek, if they meet minimum standards, have many individuals with the growth potential needed to maintain vigorous crown development necessary for genetic expression of early acorn production.

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GROWTH AND DEVELOPMENT OF OUTPLANTED HIGH-QUALITY NORTHERN RED OAK SEEDLINGS AND THE EFFECTS OF COMPETING HERBACEOUS PRODUCTION WITHIN FOUR OVERSTORY TREATMENTS – FIRST-YEAR RESULTS

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Abstract—Historically, oak (*Quercus* spp.) regeneration success on highly productive hardwood sites can be described as highly variable. Research has shown that establishing large advance oak regeneration prior to overstory removal is necessary to maintain oak populations in future stands. However, experience indicates that forest landowners are typically unwilling to wait the necessary time to develop natural advance oak reproduction, instead allowing markets to dictate harvest times. This fact necessitates the use of artificial oak regeneration to maintain oak as an important component of future stands. To date, the success of artificial oak regeneration has also been highly variable. To develop an improved understanding and enhanced methods of artificial oak regeneration, we examined the growth of outplanted, high-quality, locally adapted, 1-0 northern red oak (*Q. rubra* L.) seedlings and the effects of competing herbaceous vegetation after four overstory treatments (no cut, high grade, commercial clearcut, two age) at the Ames Plantation in west Tennessee. Sixty seedlings from 2 genetic families were outplanted within each of twelve 2-acre treatment units, resulting in 3 replicates of the 4 treatments. Initial height, root collar diameter, and number of first-order lateral roots were recorded for each seedling. Outplantings were monitored monthly during the growing season. This paper compares the first year seedling growth patterns (height and root collar diameter growth) and the impacts of competing herbaceous vegetation with emphasis on an exotic, Asian annual C_4 grass. The silvicultural implications of seedling development over the four treatment areas are evaluated.

INTRODUCTION

The topic of successful regeneration of oak (*Quercus* spp.) has acquired great attention and generated numerous research papers over past decades. However, the successional replacement of oak persists as a major concern in eastern deciduous forests, particularly on mesic or highly productive hardwood sites. Research suggests that oaks historically persisted on productive sites due to a disturbance regime that included repetitive low to moderate intensity fire events (Delcourt and Delcourt 1997, 1998, Johnson 1993a, Van Lear and Janet 1992), which no longer exists in eastern deciduous forests (Delcourt and Delcourt 1997, Lorimer 2001, Van Lear and Janet 1992). Presently, obtaining oak reproduction within intrinsic accumulator systems (areas with a high propensity to accumulate advance reproduction, generally poor quality sites) is not difficult (Crow 1988, Johnson 1993b, Rogers and others 1993). However, after a heavy overstory removal on highly productive sites (generally site index at base age 50 of > 70 feet), oaks are out-competed by other hardwood species and are quickly replaced or relegated to subordinate positions in the canopy (Clatterbuck and others 1999, Johnson 1993a).

Research has demonstrated the need for the presence of large advance reproduction prior to final overstory removals (Johnson 1993b, Loftis 1982, 1983, Sander 1971). However, experience has shown that many nonindustrial private forest (NIPF) landowners within the eastern deciduous forest region are unwilling to take the necessary steps to ensure adequate advance oak reproduction. Instead, short-term economics tend to drive forest land management decisions, including harvest times, resulting in highly exploitive practices that in turn negatively impact oak composition in future stands. The unwillingness of NIPF landowners to culture advance oak reproduction, coupled with common exploitive forest practices, presents a need for focus on post-harvest alternatives of increasing or developing oak regeneration. A shift toward a model that emphasizes the use of artificial regeneration appears to hold promise.

Furthermore, highly invasive exotic species are beginning to present additional obstacles when attempting to establish reproduction, both natural and artificial. *Microstegium vimineum* Trinches, an exotic, shade tolerant Asian annual C_4 grass, has invaded many hardwood sites from floodplains to mesic slopes (Barden 1987) and can potentially be a problem for private landowners, land managers, and foresters.

Over the past 10 years, a number of research projects have focused on the use of nursery grown seedlings to enhance post-harvest oak composition with varying results. Deer herbivory (Buckley and others 1998), herbaceous competition including exotic species (Dubois and others 2000), and competition by other woody species (McGee and Loftis 1986) have hindered success. Therefore, seedlings capable of hastened growth to attain a competitive advantage on highly productive sites are needed. Concomitantly, genetic families exhibiting growth advantages in seedling development should be identified. Currently, protocol exists for the

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

production of "advance regeneration" in the nursery (Kormanik and others 1994a, 1994b; Schlarbaum and others 1998). Through genetic selection, use of proper seed source and the optimal nursery techniques, potentially successful high quality seedlings can be developed. This study was undertaken to investigate the growth of such high quality seedlings developed by the University of Tennessee Tree Improvement Program and outplanted within four overstory treatments. We also considered the potential impacts of *Microstegium vimineum* on seedling growth and establishment.

MATERIALS AND METHODS

Study Site

The study site is located along an intermittent stream in the headwaters region of the North Fork of the Wolf River (NFWR) on the Ames Plantation in southwest Tennessee (35°09´ N, 89°13´ W). The site encompasses approximately 100 acres of mixed bottomland and riparian hardwood forest dominated by various oak species. Two distinct landforms were identified within the study site: a minor bottom near the confluence of the stream with the NFWR and ancestral terraces of the minor stream (Hodges 1997).

The headwaters region of the NFWR is located within the Mississippi Embayment of the Gulf Coastal Plainches. The geology is dominated by the highly erodible Wilcox and Claiborne formations of Tertiary age exposed by the erosion of Quaternary and Tertiary fluvial deposits and the overlying Pleistocene loess deposits common in western Tennessee (Fenneman 1938, Safford 1869). The principal soil groups are Grenada-Loring-Memphis on the terraces and Falaya-Waverly-Collins within the minor bottom (U.S. Department of Agriculture 1964).

Average site index, base age 50 years, was estimated to be 75 for oaks, 85 for yellow-poplar (*Liriodendron tulipifera* L.), and 70 for sweetgum (*Liquidambar styraciflua* L.) on both sites. Average age for the dominant and co-dominant stems across the study site was 70 years.

Study Design

In the fall of 2001, three experimental blocks were identified based on landform and position. Significant differences in average stand basal area ($p < 0.05$) were found among the blocks. Twelve 2-acre treatment units were designated within the experimental blocks and four units located within the minor bottom (Bottom block) and eight units located within the terrace sites upstream from the minor bottom (four each within the East and West blocks). Species composition at the time of establishment was dominated by oak on the ancestral terraces and yellow-poplar and sweetgum in the Bottom block. Importance values were calculated (sum of relative dominance, relative frequency and relative density) for the common midstory and overstory species located within each block (table 1).

Four overstory treatments, including a control (no cut), with 3 replications were randomly assigned to the 12 units using a randomized complete block (RCB) design. Harvesting for all treatments was completed in the winter of 2001-02. Overstory treatments are described.

Table 1—Pre-harvest importance values[a] for common species of the three experimental blocks within the oak regeneration study on Ames Plantation, Fayette County, Tennessee

	Experimental block		
Species	East	West	Bottom
American elm	11.41	6.74	21.91
A. sycamore			4.49
Black cherry	6.35		
Black oak			5.52
Blackgum	9.10		
Boxelder			16.98
Cherrybark oak	20.48	6.64	27.47
Dogwood	10.32	15.52	8.13
E. redcedar	11.34		
Green ash	11.26		
Mock. hickory	6.09	18.21	4.73
N. red oak		19.90	
Osage-orange			4.09
Persimmon			6.28
Post oak	42.48	44.36	
Red maple		6.24	4.08
Red mulberry	8.62	4.99	4.03
Redbud			4.08
River birch			7.27
Sassafras	9.25	10.21	
Slippery elm			4.55
S. red oak	77.60	18.30	9.85
Sweetgum	17.49	22.08	49.58
Walnut	14.27	15.85	
White oak	17.02	82.32	5.57
Winged elm			15.90
Yellow-poplar	26.92	28.64	95.49

[a] Sum of relative dominance, relative density, and relative frequency.

- Commercial clearcut—is defined by the removal of all stems greater than 6 inches diameter breast height (d.b.h.). This treatment is designed to represent a common practice on industrial forest land.
- High grade—is a standard diameter limit cut where all stems greater then 14 inches d.b.h. are removed. This treatment is designed to represent a common and persistent practice on NIPF lands.
- Two age—is where a residual stand basal area of 15-20 square feet per acre was targeted. Residual stems were chosen based on spacing criteria and the desire to leave stems of desirable species with an opportunity to increase in value. Desirable species included oaks, hickories (*Carya* spp.) and yellow-poplar.
- No cut—is designed to act as the study control.

Seedlings

Seedlings originating from two genetic families (families 321 and 234) in a seedling seed orchard on the Ames Plantation (Schlarbaum and others 1998) were chosen for planting following harvest. The seedlings were grown at the

Georgia Forestry Commission's Flint River Nursery under fertilization and irrigation protocols developed by Kormanik and others (1994a). The seedlings were lifted in February 2002 and were graded using procedures developed by Kormanik and others (1994a, 1994b), as modified by Clark and others (2000). The seedlings were measured for height and root collar diameter (rcd) growth, the number of first-order lateral roots (folr) *sensu* (Ruehle and Kormanik 1986), and were counted and visually classified into one of three categories (cull, good, premium). Thirty seedlings from the good and premium classes in each family were planted by shovel (20 by 20 feet) in March 2002 within each of the 12 units for a total of 720 seedlings. Mean initial rcd, initial shoot height, and number of folr for premium seedlings (n = 216) were 0.50 inches, 4.06 feet, and 21, respectively. Mean initial rcd, initial shoot height and number of folr for good seedlings (n = 504) were 0.40 inches, 3.41 feet, and 16, respectively.

The planted seedlings were monitored monthly (35-45 days) throughout the growing season for a total of four periods. Seedling condition (signs of mortality and browse pressure) was monitored for all seedlings in all four periods. Seedling mortality was defined by no presence of green tissue along the stem. Browse pressure was defined as any browse on either the terminal or lateral shoots. Shoot growth measurements were recorded for one-half of all planted material the last three periods to quantify early-, mid-, and late-season growth. Mortality and end-of-season growth data (height and rcd) were obtained in January 2003 for all seedlings after seedlings entered dormancy following the first growing season.

Herbaceous Biomass

In conjunction with the collection of growth data, herbaceous biomass production was measured in the same periods. Five randomly placed 18 square inch samples were collected within each unit for a total of 60 samples for each of 4 measurement periods. All material was clipped at ground level, categorized, dried, and weighed according to procedures in Mueller-Dombois and Ellenberg (1974).

Analysis

Differences among treatment means in seedling height growth, rcd growth, browse pressure and seedling mortality were analyzed through ANOVA and Tukey-Kramer Multiple-Comparison tests (SAS Institute Inc. 1989; NCSS 2001) with an error level of $\alpha = 0.05$ set to indicate significant differences. Three independent simple linear regression analyses were used to explore possible relationships between end-of-season seedling height growth and total herbaceous biomass production, percent *Microstegium vimineum* production and seedling browse pressure.

RESULTS

The harvest resulted in a mean basal area of 142, 20, 14, and 0 square feet per acre for the no-cut, high-grade, two-age and commercial clearcut treatments, respectively (material greater than 6 inches). Little difference in mean basal area existed between the high-grade and two-age treatments; however spacing and species composition of the residual stand differed between the two treatments due to harvest criteria. The light environment in the no-cut treatment was dark with minimal light reaching the forest floor.

No significant difference existed between genetic family, seedling quality class, or treatment for time of bud break. More than 99 percent of planted seedlings experienced bud break prior to May 4, 2002.

End of growing season mortality for all seedlings was significantly greatest for the no-cut treatment with mean percent mortality of 33 percent (n = 180, $p = 0.004$) followed by the high-grade and two-age treatments with 5 percent each. The commercial clearcut experienced no seedling mortality. Tukey-Kramer comparisons resulted in no difference between the three overstory cut treatments. No significant differences in mortality were observed between genetic families ($p > 0.05$) with mean percent mortality of 11 percent for each family.

After one growing season, height growth was significantly greater for the no-cut treatment ($p = 0.0005$). Mean growth was observed as 4.90, 5.31, 3.61, and 8.80 inches for the commercial clearcut, high-grade, two-age, and no-cut treatments, respectively (table 2). Tukey-Kramer analysis resulted in no strong differences between the three cut treatments. No significant differences in mean height growth were observed between genetic families ($p = 0.68$) with mean height growth of 5.69 and 5.61 inches for families 234 and 321 respectively. Mean growth for all Premium seedlings was greater than Good seedlings ($p < 0.001$). Mean growth for Premium and Good seedlings was 7.12 and 5.02 inches, respectively. Mean height growth differed between blocks ($p < 0.0001$) with mean height growth of 6.98, 6.42, and 3.54 inches for the East, West and Bottom blocks, respectively.

A similar pattern to that of end-of-season growth existed for early growing season growth with 81 percent of all seedlings having only one growth flush. Height growth for the no-cut treatment was significantly greater than the cut treatments ($p = 0.0008$) with mean growth of 4.88 inches, 4.51, 3.44, and 10.32 inches for the commercial clearcut, high-grade, two-age and no-cut treatments, respectively (table 2). Again, no significant differences were observed between the cut treatments. Mid-season growth was significantly different between treatments ($p = 0.009$). The commercial clearcut and high-grade treatments differed from the two-age and no-cut treatments with mean mid-season growth of 1.25, 1.35, 0.0, and –0.07 inches, respectively. Late-season growth was not different across treatments ($p = 0.53$).

Root collar diameter (rcd) growth after one growing season differed between treatments ($p = 0.03$). Mean rcd growth observed for the commercial clearcut, high-grade, two-age and no-cut treatments were 0.026, 0.013, 0.007, and –0.022 inches, respectively. Tukey-Kramer mean comparison analysis revealed significant differences between the no-cut treatment and commercial clearcut differing from one another. However, neither the no-cut nor the commercial clearcut treatment differed from the high-grade or two-age treatments at the $\alpha = 0.05$ level.

Table 2—Initial height, average height growth, and total height growth (inches) of 1-0 high-quality northern red oak (*Quercus rubra* L.) seedlings for each sampling period during the 2002-growing season for each treatment and block for the oak regeneration study on Ames Plantation, Fayette County, Tennessee

Treatment	Initial height[a]		Period of growth: Early		Mid		Late		Total growth	
Commercial clearcut	43.50	(180)[b]	4.88 A[d]	(89)	1.25 A	(41)	0.36	(43)	4.90 A	(180)
High grade	42.83	(180)	4.51 A	(91)	1.35 A	(30)	2.42	(33)	5.31 A	(171)
Two age	43.15	(180)	3.44 A	(92)	0.00 B	(27)	-1.10	(28)	3.61 A	(170)
No cut	43.58	(180)	10.32 B	(90)	-0.07 B	(20)	-0.08	(30)	8.80 B	(121)
	p = 0.89[c]		p < 0.0008		p < 0.01		p = 0.52		p < 0.0006	
Block										
East	43.19	(240)	6.57	(119)	1.13	(38)	0.39	(40)	6.98	(222)
West	43.41	(240)	6.14	(121)	0.65	(57)	0.23	(65)	6.44	(213)
Bottom	43.20	(240)	4.65	(122)	0.11	(23)	-3.05	(29)	3.54	(207)
	p = 0.92		p < 0.04		p = 0.85		p = 0.98		p < 0.0001	

[a] Sample dates: Initial = 2/08/02; Early = 6/10/02; Mid = 7/14/02; Late = 8/25/02; End = 1/04/03.

[b] Sample size (n), 50 percent of seedlings were randomly measured at each period during the growing season with n representing the number of actual seedlings in the sample cross-referenced directly from previous sample. Total height growth was measured at the end of the growing season for all seedlings.

[c] Mixed model ANOVA results.

[d] Mean separation by Tukey-Kramer multiple comparison tests. Means followed by the same letter are not significantly different at the α = 0.05 level.

Total herbaceous biomass production and end-of-season height growth were significantly negatively related across treatments; however, total herbaceous biomass production was only a moderate to weak predictor of end-of-season height growth ($r^2 = 0.55$, $p = 0.006$, r = -0.74). Herbaceous biomass production appeared to have a strong negative relationship with total height growth (r = -0.74). Mean total herbaceous biomass production differed across treatments ($p = 0.003$). Mean production was greatest within the two-age treatment, measuring 6,336 pounds per acre followed by the commercial clearcut, high-grade, and no-cut treatments with 4,793, 3,391, and 567 pounds per acre, respectively.

Microstegium production within some units of the study was extremely high. Although a strongly negative relationship was found between *Microstegium vimineum* production and mean seedling height growth within individual units, percent *Microstegium* appeared to be only a moderate to weak predictor of end-of-season seedling height growth ($r^2 = 0.54$, $p = 0.006$, r = -0.74). Although no differences in percent *Microstegium* production were found between treatments (p = 0.29), mean production ranged from 45 percent of total herbaceous biomass in the two-age treatment followed by the commercial clearcut, high-grade, and no-cut treatments with 37, 24, and 23 percent, respectively. Significant differences in mean percent *M. vimineum* biomass production occurred between blocks ($p = 0.0004$) and associated variation is accounted for in the blocking design.

When examined independently of all other variables, browse pressure accounted for approximately 67 percent of the variation in total seedling height growth ($r^2 = 0.6720$) with a slope different from zero ($p = 0.011$). Total browse pressure exhibited a strong negative relationship (r = -0.82) with total growth. Differences in seedling browse pressure were observed among blocks ($p = 0.006$), with mean number of seedlings browsed equaling 13, 21, and 34 for the East, West and Bottom blocks, respectively. Differences were observed among treatments ($p < 0.02$) due to the decrease of browse pressure experienced by the no-cut treatment. No differences in browse pressure were observed among the three cut treatments. Herbivory was concentrated in the early part of the growing season and was not recurrent. No additional browse was observed after the May observation date.

DISCUSSION

The results indicated that using high quality, large oak seedlings to maintain oak on highly productive sites with the four harvesting treatments studied appears promising. These seedlings had greater initial height and good first growing season rates of height growth. Light availability, seedling quality, and herbaceous competition along with browse pressure appear to be important factors contributing to seedling development in this study.

One of the key benefits in using high quality seedlings was the capability of seedlings to exceed browse height more rapidly due to their greater initial height at the time of outplanting. After the first growing season, heights of many seedlings, particularly the Premium seedlings, had already surpassed the “browse line” (approx. 4.5 feet). If the extra cost incurred by culling a larger number of smaller seedlings is not prohibitive, the use of only Premium seedlings may supply additional benefits. Furthermore, planting high quality seedlings may allow a reduction in the total number planted per acre, thereby reducing the total cost. However, planting high quality seedlings with current procedures

generally presents a larger initial investment. Planting fewer stems per acre (108 stems per acre on 20 by 20 foot spacing as in this study) may also reduce seedling apparency and minimize herbivory. Although browse levels were greater early in the growing season, protection appeared to be realized owing to the cessation of herbivory once the herbaceous vegetation flushed.

Most of the increase in seedling height occurred early in the growing season in conjunction with the first growth flush. Although individuals with multiple flushes were identified, these seedlings did not comprise a very large number of the population. However, the majority of the seedlings experienced only one growth flush during the first growing season. End-of-season growth differed only when comparing the no-cut treatment with all-cut treatments. The three cut treatments experienced similar growth rates. Kramer and Kozlowski (1960) found that photosynthetic rates increased with increasing light availability, yet began to level at approximately 1/3 of full sunlight. Therefore, it is not surprising that differences were not detected after one growing season. One growing season may not be adequate for the planted seedlings within the harvested units to express variable growth potential until crowns of residual overstory canopies respond to increased growing space. Additionally, a lag in response may be attributed to the allocation of resources to the root system.

Comparatively, the no-cut treatment experienced the greatest growth. However, growth was etiolated, and the seedlings appeared to succumb to the low light environment created by the intact forest canopy and dense midstory. According to McGee (1968), seedlings under dense full canopies have fewer leaves and less mass. Although no photosynthetically active radiation (PAR) measurements were taken in this study, Johnson and others (2002) found that light levels of dense canopies often fall below 2 percent of full sunlight. Multiple factors may have contributed to seedling mortality including herbivory, herbaceous competition and limited light resources. However, overstory shade is probably the major factor. This would suggest that pre-harvest enrichment planting might not be favorable if higher mortality rates are unacceptable. In contrast, the open environment created by the three cut treatments realized very little mortality in the first year.

Herbaceous competition, particularly M. *vimineum*, has a significantly negative impact on seedling growth. However, the herbaceous growth may be culpable for the cessation of herbivory. The post-harvest release of this exotic grass appeared as an “explosion” due to the species’ ability to completely overwhelm the invaded site. Although, herbaceous biomass affected seedling height performance and provided some benefit with the cessation of herbivory, M. *vimineum* will probably become the overriding herbaceous competition impacting future seedling growth.

While these results appear positive, only first-year growth has been observed and reported. Further examination and research as seedling development continues will prove informative. Differences between treatments, genetic stock and seedling quality might become more apparent as development continues. Not only herbaceous competition but competition from woody species along with a more detailed investigation of the competitive effects of M. *vimineum* should be further studied.

CONCLUSION

A model emphasizing post-harvest enrichment planting of high quality oak seedlings is a management alternative for maintaining oak as a important component on highly productive sites. High-quality oak seedlings used in this research have exhibited good growth and may aid in re-establishing oaks on this site.

Highly productive or mesic hardwood sites generally include complex species mixtures (Johnson and others 2002) and pose greater uncertainty to sustaining oak dominated forests. Johnson and others (2002) state that each step of the oak regeneration process is plagued with difficulties and unknowns. The use of high quality seedlings for post-harvest enrichment planting may aid in reducing the number of necessary steps, unknowns, and difficulties in establishing a new cohort of oaks on these sites.

ACKNOWLEDGMENTS

Funding and support for this research was provided by the USDA Initiative for Future Agriculture and Food Systems, The University of Tennessee Department of Forestry, Wildlife and Fisheries, Ames Plantation and the Hobart Ames Foundation and the Tennessee Tree Improvement Program. We would like to thank the John Rennie, Arnold Saxton and Sonja Oswalt for their review of this manuscript.

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IMPROVING SPECIES COMPOSITION IN MISMANAGED BOTTOMLAND HARDWOOD STANDS IN WESTERN ALABAMA

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Abstract—Forests of the Coastal Plain of Alabama are among the most diverse, productive, and complex in the United States. Long-term mismanagement, however, coupled with a lack of refined scientific knowledge on bottomland oak silvical characteristics and on their regeneration dynamics, has resulted in a reduction in both the quantity and quality of the oak component in many of these stands. A study was implemented in western Alabama to compare survival, growth, and animal browse of planted Nuttall oak seedlings using plastic tube shelters, wire browse protection, fertilization, mulch mats, and control. Treatment effects on seedling height and caliper growth indicate that fertilization application and type of seedling protection significantly affect both groundline diameter and height. The use of seedling protection positively affected tree growth form and protected seedlings from herbivory compared to those unprotected.

INTRODUCTION

There are thousands of mismanaged acres of bottomland forests that exist in Alabama today from past highgrading and other destructive practices. As a result, the proportion and quality of oaks retained in these forest stands has been diminished. The consequence has been the establishment of a higher fraction of stems that are composed of non-oak and other undesirable tree species. Stands that typically have included moderate proportions of high-value tree species, such as cherrybark and Nuttall oak, have been reduced to mixed-species stands of lower economic value.

A decrease in the number of mature oaks growing on productive bottomland hardwood sites can create special problems in successfully regenerating them after a harvest. Even when good seed years occur, the stocking densities and spatial arrangement of oak reproduction is sporadic at best and sometimes non-existent. Much of this is due to a lack of silvical knowledge concerning the natural reproduction dynamics of oaks within these productive sites. Limited knowledge of the formulae to successfully recruit and establish oak seedlings is largely stochastic in nature; that is, we know what silvicultural methods should encourage oak seedlings to become established, but success cannot be predicted with any certainty. As a result, numerous plant species have been able to capitalize on the high light environments created during harvest operations.

Many plant species that have the ability to flourish in these highly productive bottomland hardwood forests are shade tolerant (e.g. *Carpinus caroliniana, Halesia diptera*, etc.). This is one of the primary reasons that oak regeneration is futile in these environments. Stand prescriptions that encourage oak regeneration are often similar to those that favor the development of potentially faster growing competitor species (Kormanik and others 1995). The ramifications are that oak reproduction is often subject to well-developed understories dominated by shade tolerant species. The lower stratum of these forests often includes *Vitis, Smilax, Arundinaria*, and numerous other tolerant non-commercial tree species. These undesirable species have the ability, unlike the oaks, to become established and persist in an understory almost completely lacking in direct sunlight for many years. As a result, these species create a dense mat of vegetation that covers the forest floor so completely that penetration by direct sunlight is almost fully impeded.

These predicaments are extremely problematic for bottomland oak seedlings, because they are notoriously slow in attaining the vertical height required to rise above this layer of vegetation. They are so slow, in fact, that even when ample light is available they still are shorter in height relative to adjacent vegetation. A large proportion of oak reproduction present in this type of understory usually experiences mortality caused, at least in part, by their inability to become fully established. Extreme low-light environments at the ground level in these forests creates a situation where many desirable oak species cannot compete successfully for the necessary light, nutrients, and other resources that limit plant growth.

The initial inability of oak seedlings to grow rapidly in height makes them especially vulnerable to animal browse. Although a number of seedlings experience mortality due to stresses associated with competing vegetation, there still are many that become established in these conditions. Those seedlings unable to rise above 1.25 m (Castleberry and others 1999) however, will in many instances experience heavy browse pressure from the high population densities of both white-tailed deer (*Odocoileus virginianus*) and feral pigs (*Sus scrofa*). The potential impact of animal browse on desirable hardwood regeneration is poorly understood. Herbivory of naturally-regenerated commercial species has adversely impacted other habitat types by changes in species composition (Anderson and Loucks 1979, Hough 1965, Marquis 1981, Ross and others 1970, Tilghman 1989, Walters 1993). The presence of these animals makes it especially difficult to regenerate valuable timber, because they feed heavily on seedlings and sprouts

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

of preferred species. These problems are further exacerbated by the fact that these animals tend to stay within small pockets in the forest until the area is overbrowsed (Moore and Johnson 1967). Although light browsing usually will have no detrimental effects on the future stands in these areas, heavy browse damage can potentially lead to stem deformities, changes in species composition, reduced stocking, or extended rotations.

High population densities of herbivores and heavily shaded understory environments in mature forests have led to oak regeneration failures (Gillespie and others 1996) and stimulated an increase in the number of stems of undesirable species. In southern forests, undesirable shade-tolerant species have been increasing in dominance over time at the expense of the oak component. The fate of these forests that were once heavily stocked with oak trees is in question; quality oak seedlings are now scarce, and sapling-size specimens are virtually non-existent. Techniques to recruit oak reproduction using natural regeneration methods are still being developed and, as yet, are not reliable.

If some assurance of oak species' stature in recently cutover floodplain forests is desired, the supplemental establishment of oaks through planted seedlings could partially alleviate some of the problems associated with natural regeneration methods (species composition, density, spatial distribution, etc.) (Pope 1993). In order for artificial oak regeneration to be successful, however, two factors need to be considered: (1) faster growing competitor species (vines, herbaceous weeds and undesirable tree species), and (2) high population densities of both white-tailed deer and feral pigs.

Rapid early height growth is the key to overcoming both herbivory and the dense mat of vegetation that is present in the lower strata of these forests. In an effort to promote this growth, some measure of seedling protection may be necessary to ensure that plantings are successful. Efforts to protect seedlings from animal browse damage led to the invention of plastic tree shelters in England in 1979. These plastic tubes were approximately 4 feet tall and allowed enough light to the seedling so they were able to survive and become established, and also protected seedlings from animal browse until they emerged from the end of the tube. Not only did the tree shelters protect seedlings from browse damage, but improved seedling survival and rapid early height growth were also observed (Manchester and others 1988). Since that time, many different styles of tree protection devices have been tested throughout the world. In the United States, research programs in Michigan have shown that tube shelters effectively increased oak seedling survival and early height growth (Lantagne 1995, Lantagne and Miller 1997, Lantagne and others 1990). Comparable tests in North Carolina, Pennsylvania, and Connecticut also showed similar trends (Manchester and others 1988, Walters 1993, Ward and others 2000). In the Southeastern United States, several studies have investigated the effectiveness of tree shelters in urban environments (West and others 1999, West and others 2002) and in abandoned agricultural fields as a method of reforestation (Schweitzer and others 1999) with excellent success. While Dubois and others (2000) investigated the growth and establishment of cherrybark oak in a harvested area in eastern Alabama, there have been no reportings of tree shelters being used to aid in the establishment of bottomland oak species on recently cutover bottomland hardwood floodplain forests.

If protection from animal browse is the main factor limiting oak regeneration success, then any method of seedling protection (i.e., tube shelters or wire cages, for example) should afford similar results. However, if plastic tube shelters can stimulate greater height growth than by browse protection alone, then their use in southern bottomland forests should be encouraged. Our objectives were to examine the synergy of browse protection type and enhanced height growth on oak reproduction at the site of a recent clearcut in west Alabama. Specifically, we investigated the difference in the growth, survival, and animal browse intensity on planted Nuttall oak (*Quercus nuttallii* L.) that have been subjected to various combinations of plastic tree shelters, wire cages, and fertilization.

METHODS AND PROCEDURES

Nuttall oak seedlings were purchased in January 2000 and stored in a cooler at 40 °C until they were transported to the planting site. Prior to outplanting, the root systems of each seedling were dipped in a 10 g solution of Viterra™ to aid in keeping the roots moist.

This study was conducted in a second-bottom mixed hardwood community adjacent to the Black Warrior River in Greene County, AL, approximately 10 miles due north of Demopolis. The landowners' intent originally was to plant the area with pine. As a result, the area was clearcut and the site prepared by shearing and windrowing following logging operations. Pre-harvest vegetation on the study area ranged from the swamp chestnut oak/cherrybark oak type on drier sites to the willow/water-laurel oak type on wetter sites (Shropshire 1980). The swamp chestnut/cherrybark stands contained a large proportion of water oak (*Quercus nigra* L.) and sweetgum (*Liquidambar styraciflua* L.) but also included green ash (*Fraxinus pennsylvanica* Marsh.), white oak (*Q. alba* L.) and hickory species (*Carya* spp.). Also present in smaller numbers were American elm (*Ulmus americana* L.), winged elm (*U. alata* Michx.), and southern red oak (*Q. falcata* Michx. var. *falcata*) (Shropshire 1980).

Two planting areas were located in close proximity to each other, situated with an east-west orientation, and separated by a windrow approximately 3 m in width. A portable laser-distancing device and flagging were used to delimit each planting area and to establish planting rows. The planting area on the north side of the windrow measured approximately 82 m by 40 m and accommodated six planting rows. The planting area south of the windrow measured approximately 90 m by 41 m and received seven planting rows. Each planting spot within each row was then differentiated using color-coded pin flags to discern which treatment was to be applied at each particular location. In the spring of 2000, a total of 324 Nuttall oaks were planted in holes dug using a portable gas-powered auger with a 15 cm bit. A total of 144 seedlings were planted on the north side of the windrow, while 180 were planted on the south side.

Seedlings were watered one time with approximately two cups of water 1 week after planting to aid in their establishment due to a coincident drought. After planting, baseline measures of seedling height and groundline diameter were recorded. Groundline diameter was measured at approximately 2.5 cm above true groundline to avoid swelling that is common at the base of all trees. Seedling height and groundline diameter data were again measured at the end of each growing season in October 2000, 2001, and 2002. Due to the high population density of both white-tailed deer and feral pigs, a measure of browse intensity was documented as well. Browse incidence was quantified based on the presence or absence of the terminal bud and the amount of forking along the seedling bole as a result of herbivory. Treatment differences were tested at the $\alpha = 0.05$ level.

Herbicides were applied around seedlings of each protection type several times during the first two growing seasons to control competing vegetation. The first application was in May 2000 using a 4 percent (by volume) RoundUp Pro™ solution. To more effectively control some of the more tolerant weed species, subsequent herbicide applications were amended with 0.5 percent (by volume) of an additional surfactant (Timberland 90™). Applications were made in late June and August of 2000, and May and July of 2001. Most competing vegetation was controlled by the use of the chemicals, but some stems were manually severed.

EXPERIMENTAL DESIGN

Three hundred twenty-four Nuttall oaks were planted in a completely randomized design at the study area in February 2000 at 3 m by 6 m spacing. One-third of the seedlings were placed in 1.2 m tall opaque plastic tube shelters, one-third in 1.2-m-tall wire cages, and the remaining one-third of the seedlings were unprotected. One-half of all seedlings within each treatment received 2 10-gram fertilizer tablets (20-10-5, NPK) at the time of planting, for a total of six treatment combinations with 54 seedlings each. Black plastic mulch mats (approximately 1 m by 1 m) were employed at each planting hole across the study to further reduce the effects of competing vegetation.

RESULTS

Of the 324 Nuttall oak seedlings planted for this experiment in spring 2000, 309 (95.4 percent) were still alive after two growing seasons. While there were no significant differences in survival among treatments, 18.75 percent (3) of the seedlings that died were from the control group while 43.75 percent (7) and 37.5 percent (6) were from the wire cage and tube shelter protection type, respectively. Sixty-two percent (10) of the seedlings that experienced mortality had received a one-time fertilizer application at the time of planting, 38 percent (6) had not.

General Linear Model analyses ($\alpha = 0.05$) were used to examine the relationships between treatment/protection type and seedling height and groundline diameter growth after two growing seasons. Height growth differed significantly ($P < 0.0001$) among treatments (fig. 1). Treatment type was significant ($P < 0.0001$) as was fertilizer use ($P = 0.0019$). Groundline diameter growth differed significantly ($P < 0.0001$) between the different treatment combinations (fig. 2). Treatment type was significant ($P < 0.0001$) as was fertilizer use ($P = 0.0002$).

Duncan's Multiple Range Tests indicate the use of plastic tube shelters stimulated significantly greater height growth among seedlings than either the use of wire cages or control (table 1). Height growth by seedlings in wire cage protection was also significantly greater than for those in the control group, and fertilized seedlings exhibited greater height growth after two growing seasons than those unfertilized. Groundline diameter was also affected by seedling

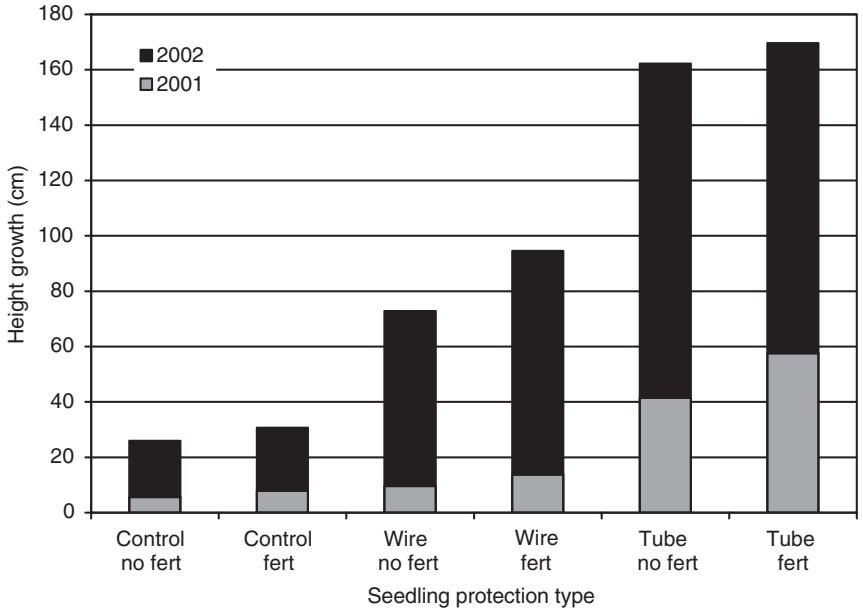

Figure 1—Height growth (cm) of planted Nuttall oak seedlings by seedling protection type and fertilizer use after two growing seasons.

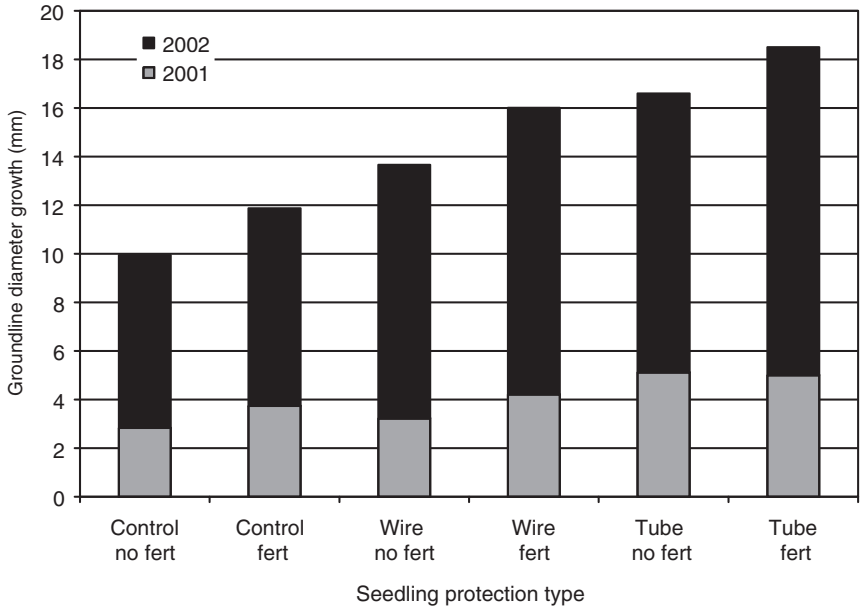

Figure 2—Groundline diameter growth (mm) of planted Nuttall oak seedlings by seedling protection type and fertilizer use after two growing seasons.

Table 1—Mean height and diameter growth of planted Nuttall oak seedlings by protection type and fertilizer use after two growing seasons

	N	Mean height[a] growth	Mean GLD growth
		cm	*mm*
Protection type			
S	102	167.18a	17.10a
W	101	84.18b	14.99b
C	105	28.46c	10.94c
Fertilizer usage			
Yes	152	99.12a	15.31a
No	156	87.43b	13.08b

S = plastic tube shelter; W = wire cage; C = control.
[a] Means followed by the same letter within the same column are not significantly different (α = 0.05) using Duncan's New Multiple Range Test.

protection type. Seedlings in plastic tube shelters were significantly larger in caliper than those in the wire cages, and seedlings in wire cages were larger than the control. Similarly, fertilized seedlings exhibited greater groundline diameter growth than unfertilized.

Analysis of variance (ANOVA) results suggest there were significant differences in herbivory among the protection types over the duration of this study. Post-hoc tests reveal that the degree of browse incidence on the control seedlings was significantly greater than either the wire cages or plastic tube shelters. Ninety-five percent of the unprotected (control) seedlings were damaged by animal browse and no longer retain their terminal buds. Twenty-eight percent of those were browsed heavy enough to cause extensive forking along the bole while 67 percent sustained only slight browse damage. In contrast, less than 5 percent of seedlings in tube shelters or wire cages sustained browse damage to the terminal leader. There were no significant differences in browse incidence between the wire cage and plastic tube treatments.

DISCUSSION

Results from the first growing season indicated that fertilizer use significantly affected seedling height growth but not groundline diameter growth. Data from the second growing season indicated that fertilizer enhanced diameter growth but not height growth. Total seedling height and diameter growth was significantly elevated by the use of fertilizer over the 2-year period. Over the course of the study the groundline diameter of seedlings increased approximately 15 percent while height growth increased 25 percent by the use of fertilizer, compared to those unfertilized. Based on these results it appears that the use of fertilizer does provide an initial boost in seedling height growth which may help them overcome the destructive influences of both competing vegetation and herbivory. Whether or not these effects are lost over time is of little importance if the initial height gains in enable seedlings to rise above browse level (1.25 m).

The use of seedling protection devices significantly increased both groundline diameter and height growth after two growing seasons. Seedlings in wire cage protection were approximately 300 percent taller than those in the control group, whereas seedling which utilized plastic tree shelters were nearly 650 percent taller than those in the control group. These figures are slightly higher than those previously reported in the literature. Lantange and Miller (1997) reported gains in height of 375 percent, and Manchester

and others (1988) report gains of 132 percent after two growing seasons for trees in shelters compared to those in the control group. Differences in growth may be attributable to the fact that those studies were done in the Northern United States where growth rates are typically slower. However, previous studies in the South also suggest height growth differentials may indeed be in the 300-400 percent range (Dubois and others 2000, Schweitzer and others 2000) even without intensive competition control. Differences in height growth between this study and others may be due to the fact that there was nearly 100 percent vegetation control surrounding all planted seedlings at this study site. In addition, there was virtually no competition for light, nutrients, or other factors that limit plant growth. This likely enhanced the growth rates and may be atypical of results found in less intensive planting regimes. The nearly complete vegetation control may also have impacted survival rates across all treatments. Some studies involving tree shelters reported high mortality rates for control seedlings (Manchester and others 1988), and this was not true for this study, where we had 95 percent survival across all treatment groups.

The intense browse pressure evidenced in seedlings in the control group may also have been an artifact of our vegetation control. There are abundant white-tailed deer in the area; however, because competing vegetation had been treated with herbicide and was either dead or dying, alternate browse was unavailable. Planted oaks were the main vegetation within the planting areas in early spring. Wire cages and plastic tube shelters protected two-thirds of the seedlings from browse with the remaining one-third of seedlings in the control group free to be browsed. This resulted in a high proportion of the control seedlings actually losing height, some by nearly 23 cm, from repeated browse since the time of planting. This not only affected tree height, but subsequent tree form was drastically altered. Control seedlings tended to be short and shrubby compared to the taller and typically single-stemmed form of protected seedlings.

The control treatment was the least costly of the protection types, but poor growth rates and tree form are an outcome of herbivory that can often lead to poor success rates in re-establishing a forest stand. Costs of both the wire cages and the plastic tube shelters are comparable but have different qualities associated with them. For example, the wire cages do protect seedlings from browse damage to the terminal leader, but do not protect seedlings from side browse as branchlets extend through the wire. As a result, cage-protected seedlings are not as straight and generally have poorer form compared to those in plastic tube shelters. Unless side branches are removed, the cage protection devices will be very difficult to remove when the seedlings rise above browse level. Plastic tube shelters are the most costly of the treatments studied, but their use ensures that requisite rapid early height growth, coupled with good tree form, can be attained for desirable species. Although not investigated, plastic tube shelters might have a lower cost per successful seedling compared to other methods.

SUMMARY

The 1.2-m-tall opaque plastic shelters stimulated both greater seedling height and groundline diameter growth over two growing seasons compared to those enclosed in wire cages or those in the control treatments. Partially as a result of the growth rate differential, tree form also was superior with increasing levels of protection with the best form attained through the use of plastic tube shelters and the worst form for seedlings in the control treatment. The effects of fertilizer on planted Nuttall oak seedlings were demonstrated through enhanced seedling height and groundline diameter growth compared to those unfertilized. Incidence of animal browse was significantly reduced by the presence of seedling protection devices. The use of protection devices and fertilizer, either separately or in concert, can enhance early seedling growth and aid in the establishment of artificially regenerated bottomland hardwood species.

ACKNOWLEDGMENTS

The authors would like to thank Mr. John Caldwell for his generous support. Additional support was provided by the Auburn University graduate school through research grants and by Capital Veneer Works through the Robert Lewis Adams Fellowship for research in hardwood management.

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EFFECTS OF SUBSOILING AND COMPETITION CONTROL ON FIRST YEAR SURVIVAL AND GROWTH OF FOUR HARDWOOD SPECIES

Andrew W. Ezell and Mark W. Shankle[1]

Abstract—Afforestation of abandoned agricultural land with hardwood seedlings is being conducted on thousands of acres in the South annually. More than 300,000 acres have been planted under the auspices of the Wetland Reserve Program, and other cost-share programs also promote the planting of hardwood species. Unfortunately, survival in many of these planting efforts has been extremely low. To evaluate the importance of cultural treatments on first-year survival, one-half of previously cultivated area was subsoiled in October 2001. The remainder of the test area was not treated mechanically. In February 2002, 1-0, bareroot seedlings of Shumard oak (*Quercus shumardii*), water oak (*Q. nigra*), willow oak (*Q. phellos*) and green ash (*Fraxinus pennsylvanica*) were planted by hand (half of each species in subsoil trenches; half in adjacent untreated areas). Oxyflurofen and sulfometuron were applied over-the-top of the planted seedlings for control of herbaceous vegetation with three replications of each species/treatment combination. Initial total height and groundline diameter (GLD) were measured for sample trees in each species/treatment plot including trees in untreated check plots. In November 2002, survival was evaluated, and height and GLD were remeasured. Subsoiling significantly increased both height and groundline diameter. Survival was not affected by any of the treatments, but differences are expected in year 2 or 3.

INTRODUCTION

Thousands of acres are planted with hardwood species each year in the South. While this regeneration practice is applied to cutover areas, a significant proportion of these acres is on "retired" agricultural land. To date, more than 300,000 acres of such land has been planted in the Lower Mississippi Alluvial Valley (Gardiner and Oliver 2002). Unfortunately, many of these acres have experienced very low survival (James 2001), and in effect, the hardwood planting effort has been of little or no value on many thousands of acres. The potential for afforestation with hardwoods is very significant. By 2040, it is estimated that more than 30 million acres of retired agricultural production land will be planted in trees (Wear and Greis 2002). Of this total, a notable portion will be planted with pines, but due to landowner disposition, site variables, and the current market for some pine products, millions of these acres are forecast to be planted with hardwoods. It is therefore extremely important that future hardwood regeneration efforts result in greater seedling survival.

The variables which must be addressed in hardwood seedling survival are seedling quality, planting quality, soil-site conditions, and competition control (Ezell and Hodges 2002). Landowners must learn to match the proper hardwood species to regeneration sites, use only high-quality seedlings, and ensure a high quality planting effort is utilized. What lies beyond the control of the land manager is the weather and resulting site conditions during the growing season. On most sites, it is virtually impossible to plan for extreme drought or flood conditions. However, the competing vegetation is known to be well-established on these former agricultural lands, and decades of cultivation or grazing are known to have created potentially negative soil conditions. Thus, this study was undertaken to evaluate the influence of both subsoiling and herbaceous competition control on the first-year survival and growth of four hardwood species.

MATERIALS AND METHODS

Study Site

The study was installed on the Mississippi Agricultural and Forestry Experiment Station near Pontotoc, MS. The site had been retired from production after decades of cultivation and/or use for pasture. At the time of study initiation, the site was occupied by a mixture of fescue, *Andropogon*, and broadleaf forbs. Such a site is truly representative of millions of acres across the South which will be planted with hardwoods.

Treatments

One-half of the study site was subsoiled in November, 2001. The subsoil trenches were installed on 10-foot centers, and the depth of the subsoiling was approximately 18 inches. The site was dry at the time of mechanical treatment, and the subsoiling would have been very successful at breaking any restrictive/compacted layers within the treatment depth.

In January, 2002, seedlings of Shumard oak, water oak, willow oak, and green ash were planted on the site. One-half of each species was planted in the subsoiled trenches, and one-half was planted in the adjacent untreated area. The plantings were arranged into three "planting blocks" with each species represented in each block. These blocks served to provide three replications of all species/competition control combinations.

In February, three competition control treatments were applied (table 1). All treatments were applied prior to any of the seedlings breaking dormancy. An untreated portion was retained for each species in each planting block. Thus,

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Table 1—List of treatments used in 2002 hardwood planting study

Treatment	Herbicide
no.	*rate per acre*
1	Goal 2XL (64 oz.)
2	Oust XP (2 oz.)
3	Goal (32 oz.) + Oust XP (1 oz.)
4	Untreated

the experimental design was four species x two soil treatments x four competition control treatments x three replications. All preemergent (February) herbicide treatments were applied in a six-foot swath over-the-top of the planted seedling using a CO_2-powered backpack sprayer with a 4-nozzle hand-held boom. Total spray volume was 20 gallons per acre. A grass herbicide (Select®) was applied in June to all herbicide treatment plots.

Data Collection and Analysis

After planting but prior to herbicide application, the aboveground height and groundline diameter (GLD) were measured on each seedling. Plots were evaluated at 60, 90, 120, and 150 days after initial herbicide treatments with an ocular estimate of percent ground cover by grass, broadleaves, or vines. At the same timings, seedlings were evaluated for any phytotoxic symptomology. In December, 2002, seedlings were evaluated for survival, height, and GLD. Data was subjected to analysis of variance (ANOVA) and means separation tests.

RESULTS

Survival

Survival ranged from 91.7 percent to 100 percent in all treatment plots. No significant differences resulted from any treatment or combination of soil/herbicide treatments. Precipitation on the study site was more than adequate during the growing season of 2002. Based on measured seedling parameters and earlier studies (Hodges and Ezell 2001), it will not be surprising to see appreciable mortality in untreated plots in the next few years.

Height Growth

Average total height for all species and treatment combinations is found in table 2. For Shumard oak, there was no significant difference among any competition control treatments within a soil treatment. However, trees in the subsoiled area were all significantly taller than those in the unsubsoiled area. Thus, the subsoiling provided adequate resources to the seedlings for growth in the first growing season.

For water oak, trees in Treatment 2 (Goal 2XL) were significantly taller than those in Treatments 1 and 3 on the subsoiled area. Otherwise, average heights in the subsoiled area were not significantly different. In the unsubsoiled area, trees in the Treatment 1 plots were significantly shorter than other treatment plots. Again, all average heights in the subsoiled area were significantly taller than those from the unsubsoiled area.

The results for willow oak were very similar to those for Shumard and water oaks. The exception to this generality was the lack of significant difference between trees in the subsoiled and unsubsoiled plots which received Treatment 1. Otherwise, trees in subsoiled areas were all significantly taller than those in unsubsoiled areas when comparing plots with the same herbicide treatment. Green ash exhibited the same trend as the oaks. Trees in the subsoiled area were significantly taller than those in the unsubsoiled area when comparing plots with the same herbicide treatments.

Table 2—Average total height and average total groundline diameter for all species by treatment (average all reps)

		Average total height				Average total groundline diameter			
Treatment	Soil trt.	SHO	WAO	WIO	GRA	SHO	WAO	WIO	GRA
no.		*-feet-*				*-inches-*			
1	Sub	2.38a	1.99b	2.14c	3.08a	0.31b	0.24a	0.33b	0.51a
	Un	1.77b	1.38d	2.07c	2.50b	0.27c	0.18b	0.27c	0.48a
2	Sub	2.26a	2.28a	2.23b	2.42b	0.30b	0.28a	0.35a	0.36b
	Un	1.78b	1.60c	2.11c	2.31c	0.27c	0.26a	0.28c	0.27c
3	Sub	2.29a	1.98b	2.34a	2.78a	0.33b	0.27a	0.39a	0.41b
	Un	1.62b	1.70c	2.14c	2.17c	0.24c	0.21b	0.32b	0.30c
4	Sub	2.30a	2.08ab	2.34a	2.89a	0.49a	0.26a	0.31b	0.41b
	Un	1.81b	1.73c	2.27b	2.18c	0.27c	0.19b	0.29bc	0.31c

SHO = Shumard oak; WAO = water oak; WIO = willow oak; GRA = green ash; Sub = subsoiled; Un = untreated.
Values in a column followed by the same letter do not differ at $\alpha = 0.05$.

Groundline Diameter

Average GLD values are found in table 2. In Shumard oak, the average GLD values were very consistent in the unsubsoiled area irrespective of herbicide treatment, and all averages were significantly less than those from the subsoiled area. The trees in the "untreated" (Treatment 4) plots had the largest average GLD in the subsoiled area, but this was the only species to exhibit this result.

For water oak, there was no significant difference between trees in subsoiled or unsubsoiled areas with Treatment 2 applications. Otherwise, all average GLDs were greater in subsoiled areas when compared to those in unsubsoiled areas.

Willow oak results differed slightly. Average GLD was always greater for trees in the subsoiled area than the unsubsoiled area when making comparisons within a treatment. The differences were all statistically significant except in the untreated (Treatment 4) plots.

Green ash trees in Treatment 1 plots (irrespective of soil treatment) all had larger GLD values than in other treatments. Once again, the trees in the subsoiled area were significantly larger than those from the subsoiled area when comparisons were made within a treatment.

SUMMARY

Subsoiling significantly increased height and GLD for the species on the study site. The adequate rainfall of the 2002 growing season is considered to be a significant factor in the lack of first-year survival differences, but that may change in years 2 or 3. All species in the study responded well to the treatments, and while competition control was known to be an important factor in hardwood establishment, it appears that subsoiling may also be very important and may be of additive value.

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OUTPLANTING OF THE ENDANGERED PONDBERRY

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Abstract—Pondberry [*Lindera melissifolia* (Walt) Blume, Lauraceae] is an endangered shrub that occurs in seasonally flooded wetlands in the Southeastern United States. We established new pondberry populations as an aid in conserving the species, whose distribution and abundance have been affected by habitat destruction and alteration. We dug equal numbers of young male and female pondberry stems from a natural population, planted them in pots, and translocated them to five protected locations in the field. After 1 year, 69 percent of the plants survived, with male and female plants surviving equally well. More than 90 percent of the surviving plants had stems that increased in height, although the height of the tallest stems decreased. Many of the plants produced new stems, but some older stems died during the year. Most of the present pondberry habitat is surrounded by agricultural fields, which significantly limits dispersal. This study shows that pondberry can be successfully outplanted, in efforts to assure survival of the species.

INTRODUCTION

Pondberry [*Lindera melissifolia* (Walt) Blume, Lauraceae] is a rare woody plant that occurs in seasonally flooded wetlands and on the edges of sinks, ponds, and depressions in the Southeastern United States (Radford and others 1968). The plant is a stoloniferous, clonal shrub that grows to 2 m in height. The species was listed as endangered by the U.S. Fish and Wildlife Service in 1986 (U.S. Fish and Wildlife Service 1986). Pondberry probably has always been rare (Kral 1983, Steyermark 1949), but the distribution and abundance of the species have been affected by habitat destruction and alteration, especially timber cutting, clearing of land, and local drainage or flooding of wetlands. Agricultural land clearing operations have severely reduced pondberry populations in Missouri and Arkansas since the 1940s [Tucker, G.E. 1984. Status report on *Lindera melissifolia* (Walt) Blume. Provided under contract to the U.S. Fish and Wildlife Service, Southeast Region, Atlanta, GA. 41 p. Unpublished manuscript. On file with: U.S. Fish and Wildlife Service, Southeast Region, 1875 Century Blvd., Suite 200, Atlanta, GA 30345]. Many of the existing pondberry colonies are quite small. The species commonly occurs in patches of woods, too wet for crops, surrounded by huge agricultural fields.

Pondberry occurs in Arkansas, Georgia, Mississippi, Missouri, North Carolina, and South Carolina, but has apparently been extirpated from Alabama, Louisiana, and possibly Florida. The 1993 pondberry recovery plan states that there are 36 populations (U.S. Fish and Wildlife Service 1993), but other colonies have been discovered since 1993 in new locations and near known populations. The current number of populations is unknown; some populations previously believed to be far enough apart to preclude interbreeding (as on the Delta National Forest, MS) may have been linked by recently discovered colonies. In addition, some colonies that were present in 1993 no longer exist. All of the plants in a colony near Cleveland, MS, recently died. Another colony on private land in eastern Arkansas was destroyed by the landowner.

Pondberry is dioecious, with small yellow flowers that bloom in spring. The plant usually occurs in clones with numerous stems, but because the species is clonal, colonies with abundant stems may contain few genets (genetic individuals) (Eriksson 1992, Oinonen 1967). Male stems outnumber female stems in most colonies, and some colonies are composed of only male clones (Wright 1989, 1990). Seed production is often sporadic, and few seedlings are observed in and around natural populations (Wright 1990), as in many clonal plant species (Cook 1979, Eriksson 1989, Harper 1977).

The purpose of our study was to investigate whether establishing new pondberry populations aids in conserving and bringing about the recovery of the species over its presumptive former range. In order for a species to survive and spread, plants must colonize unoccupied habitat at least as often as populations die out (Schemske and others 1994). The pondberry recovery plan (U.S. Fish and Wildlife Service 1993) states that the species will be downlisted when 15 protected, self-sustaining populations occur throughout the historic range of the plant. The specific objectives of this study were to examine the following questions: (a) Is it possible to transplant clonal pondberry material successfully? (b) Does percent survivorship differ among male and female plants for this species?

METHODS

During the spring flowering season, we tagged pondberry plants in a population on private land in Mississippi in order to establish gender. We separated young rooted stems from clones and dug them with soil from the area in which they grew. The stems were planted in pots; a synthetic soil mix was used to fill in around the root mass. The plants were maintained in a greenhouse for at least several weeks then translocated to the field. We translocated equal numbers of male and female plants to a total of five sites in protected locations in Mississippi. The planting sites were Leroy Percy State Park near Hollandale, two sites at Yazoo National Wildlife Refuge near Glen Allen, Morgan Brake

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

National Wildlife Refuge, and Hillside National Wildlife Refuge near Tchula. Planting sites were chosen in low areas with medium light, but not so much light that competition by other plants would be a problem. We located sites within 200 m of a trail to facilitate our watering of the plants as well as viewing by visitors. We placed the pondberry plants in slight depressions at least 3 m away from medium-to-large trees. In September 2000, plants were translocated to Leroy Percy State Park and to Yazoo National Wildlife Refuge. In November 2000, plants were translocated to Morgan Brake National Wildlife Refuge and to Hillside National Wildlife Refuge. Each pair of male and female plants was surrounded by a cage of chicken wire on wooden supports to prevent damage by animal herbivores and was labeled (fig. 1). Each plant had been previously tagged, and the height of each stem was recorded at planting. We watered the plants weekly during the growing season unless ample rainfall had occurred that week. We monitored the plants monthly for insect pests and applied pesticide and fertilizer as needed. One year after outplanting, we monitored the survival of the plants, recorded new stems, measured the height in cm of surviving and new stems, and noted whether dieback had occurred at the apex of the stem.

Figure 1—A pair of outplanted pondberry (*Lindera melissifolia)* plants surrounded by a cage for protection against animal herbivores.

RESULTS

Most of the potted plants produced new stems within a few weeks in the greenhouse, and new stems occurred on plants at every site except Morgan Brake. At one site on the Yazoo National Wildlife Refuge, animals, probably armadillos (*Dasypus novemcinctus*), tunnelled under the wire enclosures and dug up several of the plants. We replaced the plants promptly, and all survived. Most of the plants (69.2 percent overall) survived and grew (table 1). Survival was lowest at Morgan Brake (35 percent) where the plants were attacked by a scale insect that also attacked the surrounding vegetation. The percentage of surviving plants that increased in height after introduction to the sites ranged from 92.3 to 100. The percentage of plants that experienced some stem dieback ranged from 84.6 to 100. After 1 year, the mean height of the stems of surviving plants was slightly less than the height at time of planting at three of the five planting sites, and the mean number of stems decreased slightly at four of the five sites (table 2). Fisher's exact tests demonstrated no differences in survival of female vs. male plants at the sites (table 3).

DISCUSSION

The pondberry plants we translocated showed good overall survival and health except at Morgan Brake, where the plants were infested with scale. Morgan Brake was the only location where no new stems were produced, but the surviving stems grew taller than stems at the other sites. After the attack by scale insects, regrowth occurred in existing stems instead of in the production of new stems.

Although one or more stems of many of the plants increased in height, the stress of introduction and the effects of dieback apparently resulted in a decrease in mean height of the stems at three sites. New stems were produced, but

Table 1—Survival and growth of pondberry plants introduced to five protected sites in Mississippi, 1 year after translocation. Data for male and female plants are pooled. Overall survival was 69.2 percent

		Surviving plants			
			Plants with		
Site	Plants	Surviving	Height increase	New stems	Dieback
	- - number - -		*- - - - - - - - - - - - - - - - - percent - - - - - - - - - - - - - - - - -*		
Leroy Percy	20	13 (65.0)	92.3	38.5	100.0
Yazoo 1	31	26 (83.9)	92.3	54.8	84.6
Yazoo 2	10	7 (70.0)	100.0	28.6	85.7
Morgan Brake	20	7 (35.0)	100.0	0.0	85.7
Hillside	40	31 (77.5)	96.8	22.5	87.1

Table 2—Height and number of stems of pondberry at planting and 1 year after translocation. Data for male and female stems are pooled.

Location and original number of plants	At planting[a]		1 year later[a]	
	Mean			
	Height	Stems per plant	Height	Stems per plant
	cm	*number*	*cm*	*number*
Leroy Percy (20)	46.3 (29.4)	1.8 (1.2)	45.2 (27.7)	1.2 (0.4)
Yazoo1 (30)	48.2 (32.9)	2.0 (1.3)	39.2 (26.9)	2.2 (1.2)
Yazoo 2 (10)	41.8 (30.5)	1.5 (0.5)	43.9 (24.8)	1.2 (0.8)
Morgan Brake (20)	42.8 (29.6)	2.0 (1.0)	63.8 (19.8)	1.0 (0.0)
Hillside (40)	45.3 (27.7)	1.9 (1.4)	41.2 (24.7)	1.8 (1.3)

[a] Standard deviations in parentheses.

Table 3—Survival of male vs. female pondberry plants introduced to five protected sites in Mississippi, 1 year after translocation

Site	Gender	Alive	Dead	Total	Fisher's exact test (*P*)
Leroy Percy	Female	5	5	10	0.15
	Male	8	2	10	
Yazoo 1	Female	12	3	15	0.34
	Male	13	2	15	
Yazoo 2	Female	4	1	5	0.42
	Male	3	2	5	
Morgan Brake	Female	5	5	10	0.15
	Male	2	8	10	
Hillside	Female	14	6	20	0.16
	Male	17	3	20	

they were not quite equal to the number of stems that died during the year. The turnover period in stems in natural populations is unknown. The stem dieback that was noted in the introduced plants also occurred in all the natural populations that we visited. At present, the cause of dieback is not known. Three fungal species previously reported for *Lindera* were isolated from dead pondberry stems by Devall and others (2001), but the authors did not demonstrate that the fungi caused the dieback. Godt and Hamrick (1996) suggest that stem dieback in pondberry may be an aging phenomenon. Other researchers have noted dieback as well (Richardson and others 1990, Tucker 1984). Morgan (1983) recorded dieback in a pondberry population in Missouri; 20 years later dieback is still occurring at the same site, but there are thousands of stems and the population seems vigorous, indicating that pondberry plants can survive for a long period in the presence of dieback (Devall and others 2001).

Although male stems outnumber female stems in many natural populations of pondberry, and some natural populations are composed of only male stems (Richardson and others 1990, Wright 1994), the male and female plants in our study survived outplanting equally well. J. Lovett Doust and P. Lovett Doust (1988) suggest that in dioecious species, the greater physiological cost of reproduction for females may result in gender ratios biased in favor of males. Almost no flowering (two plants flowered) and no fruit production occurred in the outplanted pondberry, so the cost of reproduction has probably not affected survival in these plants.

In our study, removing individual stems from pondberry clones provided large plants for introduction to new sites within a few weeks without apparent damage to the original clones and without decreasing the genetic diversity of the natural population. One advantage of using clonal material is the decreased time and cost of maintaining plants in the greenhouse, compared with using seedlings. It would take at least 2 years for seedlings to grow to the size of clonal transplants. Larger introduced pondberry plants may also survive better than seedlings. At a site in Florida, Kent and others (2000) found that initial plant size affected survival in Britton's beargrass (*Nolina brittoniana*), scrub plum (*Prunus geniculata*), and probably scrub lupine (*Lupinus aridorum*). Size at time of planting did not affect the survival of papery whitlow-wort (*Paronychia chartacea*), but only the larger plants flowered and set seed.

The Lower Mississippi Alluvial Valley, where most of the present pondberry populations occur, is one of the most endangered ecosystems in the United States (Noss and others 1995). Much of the former forest has been cleared for agriculture, and flood control projects have drastically changed hydrological cycles (Stanturf and others 1998, 2000). Most of the potential pondberry habitat is fragmented and surrounded by agricultural fields, thus the possibility for dispersal is very limited, and populations that die out will usually not be replaced (Devall and others 2001).

Schemske and others (1994) suggest that designing and managing new populations of rare plant species is the most difficult task associated with their conservation. Introductions of rare species into new or former habitat have produced mixed results (Griffith and others 1989). Existing pondberry populations should be protected where possible, and searches for new populations should continue, but this study indicates that introduction of pondberry plants in governmentally or privately protected sites provides additional assurance of the survival of the species.

In summary, after 1 year in the field, clonal material provided successful transplants, with no difference in survivorship between male and female plants. To provide more information for future restoration, the plants in our study should be monitored for several years. Additional studies should also be undertaken to compare the survival of outplanted seedlings to the survival of outplanted stems taken from clones.

ACKNOWLEDGMENTS

We would like to thank Kay Kirkman and Dan Wilson for helpful reviews of the manuscript. We appreciate Bryce Burke's help in the field and with the cages. We also thank the personnel at Leroy Percy State Park, Yazoo National Wildlife Refuge, Morgan Brake National Wildlife Refuge, and Hillside National Wildlife Refuge for providing protected sites for the introduction of pondberry.

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GROWTH AND SURVIVAL OF BALDCYPRESS PLANTED IN AN OLD RICE FIELD OF COASTAL SOUTH CAROLINA

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Abstract—Vast acreages of baldcypress [*Taxodium distichum* (L.) Rich.] swampland in coastal South Carolina were cleared for rice production starting in the late 1600s. When rice cultivation ended in the late 1800s, many cultivated areas became marshlands. Other fields failed to return to forest unless they were planted. In one such area, nine acres were planted with baldcypress in 1956 by MeadWestvaco near Walterboro, SC. Seedlings were planted on an 8- by 8-foot spacing. Beginning in November 1991, five 0.12-acre plots were established within the stand to monitor tree growth and survival and measured yearly. In addition to baldcypress, the stand now contains red maple (*Acer rubrum* L.), black willow (*Salix nigra* Marsh.), sweetgum (*Liquidambar styraciflua* L.), and persimmon (*Diospyros virginiana* L.). The number of trees per acre declined from 600 to 402 by year 2000. Average diameter of trees after 44 years was 9.1 inches. In 2001, MeadWestvaco clearcut half of the stand, thinned 1/4 of the stand, and left 1/4 intact. All stems were removed from the clearcut section, and the thinned section was reduced to 104 stems per acre (88 percent of remaining trees are baldcypress). Five regeneration plots were placed in the clearcut area to follow future regeneration patterns.

INTRODUCTION

Almost pure stands of baldcypress [*Taxodium distichum* (L.) Rich] were found in southern coastal plain river floodplains when settlers first arrived in America (Mattoon 1915). With the introduction of rice cultivation into South Carolina in the 1600s, the upper section of river swamps was diked to create water storage ponds, and the remainder of the swamp was cleared, leveled, and planted to rice. Eventually, the demand for land and the introduction of new cultivation techniques using tidal action to flood rice fields along rivers resulted in the extension of rice cultivation as far as 35 miles inland (Edgar 1998). From 1850-1860, 227 plantations reported over 72,000 acres of land under rice cultivation (Gresham and Hook 1982).

Rice culture effectively ended in South Carolina by the end of the 19th century and was entirely through by 1936, but the old rice fields can still be identified on the landscape today. In a survey conducted in the early 1980s, Gresham and Hook (1982) found that 32 percent were still under management (mainly for waterfowl). Of the rest, 42 percent were identified as having a grass-marsh plant cover while only 26 percent had a tree-marsh plant cover. Thus it can be concluded that many of the abandoned fields have not reverted to their former baldcypress-dominated status. In some cases, the old fields were planted with baldcypress seedlings in order to re-establish stands of trees. One such plantation was planted by MeadWestvaco in 1956. Beginning in November 1991, a study was initiated to determine long-term growth rates of the trees growing in the baldcypress plantation.

MATERIALS AND METHODS

The baldcypress plantation is near Jacksonboro, SC on soils classified as fine, mixed, thermic Typic Argiaquolls. These soils are very poorly drained; they are slowly permeable soils formed in clayey sediment. These nearly level soils are typical of broad depressional areas and drainageways (Stuck 1982), and they are frequently flooded. The site was planted in February 1956. Nine acres were planted with baldcypress on an 8- by 8-foot spacing (600 trees per acre). As far as is known, no cultural treatments were done on the site after planting.

Five 0.12-acre study plots were established in the central portion of the plantation in November 1991. All trees within the plots with a diameter at breast height (d.b.h.) greater than 4 inches were identified as to species and crown class, tagged, and their d.b.h. measured. Each year since 1991, d.b.h. has been recorded at the end of the year.

In 2001, MeadWestvaco clearcut half of the stand, thinned 1/4 of the stand, and left 1/4 intact. All stems were removed from the clearcut section. All five study plots fell within the thinned portion of the stand. An additional five 0.12-acre regeneration plots were placed in the clearcut area to follow future regeneration patterns.

All data were analyzed using repeated measures Analysis of Variance (ANOVA) through the Procedures of General Linear Models (PROC GLM) on the SAS Systems software version 8.0 (SAS 1999). In addition, a special macro called PDGLM800 was used with PROC GLM to create groups of similar growth means among plots, crown classes, and time (Saxton 1998). All groups of means were compared at the level of $P < 0.05$ for test of significance.

RESULTS

In 1991 baldcypress was the dominant tree species growing on the plantation site, representing 83 percent of the total stems measured (table 1). Black willow (*Salix nigra* Marsh.) was the second most common tree (12 percent of stems), with scattered red maple (*Acer rubrum* L.), persimmon (*Diospyros virginiana* L.), swamp blackgum [*Nyssa*

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Table 1—Mean number of trees per acre by species growing in a baldcypress plantation in coastal South Carolina between 1991 and 2000

Species	1991	2000	2001
	- - - - - *number* - - - - -		
Baldcypress	400	375	92
Black willow	58	7	3
Red maple	8	7	7
Persimmon	7	5	2
Swamp blackgum	5	5	0
Sweetgum	3	2	0
Total stems/acre	481	401	104

Plots were thinned in 2001.

Table 2—Diameter growth of baldcypress among crown classes

Year	Crown class			
	D	CD	I	S
	- - - - - - - *-inches per year-* - - - - - - -			
1992	0.47a	0.35b	0.12c	0.05d
1993	0.20a	0.12b	0.02c	0.01c
1994	0.34a	0.24b	0.08c	0.05d
1995	0.44a	0.31b	0.11c	0.05d
1996	0.13a	0.08b	0.01c	-0.01c
1997	0.28a	0.24b	0.09c	0.07d
1998	0.20a	0.13b	0.04c	0.02d
1999	0.26a	0.18b	0.05c	0.03c
2000	0.07a	0.05a	0.01b	0.02b
Total	2.39a	1.70b	0.53c	0.26d

D = dominant; CD = co-dominant; I = intermediate; S = suppressed for 1992–2000. Mean values within a year with different letters are significant at 0.05 level.

sylvatica var. *biflora* (Walt.) Sarg.], and sweetgum (*Liquidambar styraciflua* L.). By the year 2000, natural mortality resulted a 17 percent decline in the number of trees per acre with the greatest decline occurring among the black willow. Eighty-eight percent of the black willow died during the 10 year period, while only 6.2 percent of all other tree species died. After the study plots were thinned in 2001, only 104 stems per acre were left. Baldcypress made up 88 percent of the total stems in the thinned stand with red maple, persimmon, and black willow making up the rest. All swamp blackgum and sweetgum were removed during thinning.

Overall, diameter growth differed significantly through time with respect to plots ($p = 0.0001$) and crown classes ($p < 0.0001$). Also, the interaction of time and crown classes ($p < 0.0001$) was significant although the time and plot interaction was not ($p = 0.3665$).

Mean diameter growth of trees within the five plots did not vary much, although trees in plot 5 tended to grow more than those in the other four plots from 1992 through 1998, with significant differences recorded in 1994 and 1996. In 1998, trees in plots 3 and 5 showed significantly greater diameter growth. During 1999 and 2000, trees in plot 3 exhibited the most diameter growth, but values were not significantly greater than other plots. There was no difference in respect to diameter growth in all five plots during 1999, while diameter growth was significantly lower in plots 1 and 2 during 2000.

When we look at the results for individual years by crown class (table 2), dominant trees grew significantly more than other crown classes (co-dominant > intermediate > suppressed) for all years except 2000. During 2000, there was no significant difference between dominant and co-dominant trees, but they still grew significantly more than intermediate and suppressed trees. In 1993, 1996, 1999, and 2000, intermediate and suppressed trees did not differ from each other in diameter growth. The growth trend among crown classes indicated that after 1996, growth differences between dominant and co-dominant trees was declining. As a result there were less significant differences among crown classes by 2000. Total baldcypress diameter growth during the study was 2.39, 1.70, 0.53, and 0.26 inches for dominant, co-dominant, intermediate, and suppressed trees, respectively. At the end of the study, mean diameter of baldcypress growing in the plantation was 9.1 inches. Dominant baldcypress averaged 13.9 inches d.b.h., while co-dominant, intermediate, and suppressed trees averaged 10.8, 6.7, and 5.0 inches, respectively.

DISCUSSION

Baldcypress is recognized as a tree species especially well-suited to planting in wet areas (Conner and others 1999, Peters and Holcombe 1951, Williston and others 1980, 1981). It thrives on a variety of soil types and tolerates flooding once established. Very little information exists on the success of plantation grown baldcypress. Krinard and Johnson (1976, 1987) do report that the average diameter of 21- and 31-year-old baldcypress growing in Mississippi was 6.1 and 8.6 inches, respectively, indicating a 10-year growth rate of 2.5 inches. This is higher than the 2 inches reported for natural stands by Mattoon (1915) and Langdon (1958) or the 1.5 inches reported by Williston (1969). In the current study, nine year growth of dominant baldcypress was 2.4 inches. Assuming similar growth for the next year, the 10-year growth rate would be similar to that reported by Krinard and Johnson (1987). Based on these rates, plantation grown baldcypress grow faster than those in natural stands.

Although baldcypress was the only species planted on the site and represented the majority of trees growing on the site, other species did become established. Most of these species are common pioneer species. Black willow is a short-lived species that rarely asserts dominance in a stand; nearly all of the individuals in the study were in the co-dominant crown class. Natural mortality is generally high with this species (Pitcher and McKnight 1990) as was observed in this study. The few remaining black willow nearly all showed signs of declining health (dead limbs,

dying tops). Red maple are a longer-lived successional species. They are tolerant of shade and are rapid growers (Walters and Yawney 1990). Diameter of dominant red maples was nearly 5 inches larger than that of dominant baldcypress. In other crown classes, there was no difference in diameter. Sweetgum is another rapidly growing pioneer species (Kormanik 1990) but not as fast a grower as red maple. Average diameter of sweetgum prior to thinning was 14.6 inches. Upon thinning, all the sweetgum and blackgum were removed from the plots as were the dominant maples.

While there are no reports of thinning studies in baldcypress plantations, studies in natural stands indicate that diameter growth can be expected to increase after thinning. Studies in Florida (Ewel and Davis 1992, McGarity 1979), Louisiana (Dicke and Toliver 1988, Toliver and others 1987), and Mississippi (Williston 1969) all report increases of around 0.5 inches in 10 year growth.

ACKNOWLEDGMENTS

Funding was provided by the McIntire-Stennis Cooperative Forestry Research Program through Clemson University. MeadWestvaco has graciously allowed access to their property for the duration of this project. In any such program of this duration, many people have helped with the field work. We especially want to thank Jeffery Vernon and Mike Gibson for field assistance and Dr. Larry Grimes for his help with the statistics. Belle W. Baruch Institute of Coastal Ecology and Forest Science Technical Contribution: 03-02.

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FLOOD PLAIN TOPOGRAPHY AFFECTS ESTABLISHMENT SUCCESS OF DIRECT-SEEDED BOTTOMLAND OAKS

Emile S. Gardiner, John D. Hodges, and T. Conner Fristoe[1]

Abstract—Five bottomland oak species were direct seeded along a topographical gradient in a flood plain to determine if environmental factors related to relative position in the flood plain influenced seedling establishment and survival. Two years after installation of the plantation, seedling establishment rates ranged from 12±1.6 (mean ± standard error) percent for overcup oak (*Quercus lyrata* Walt.) to 33±2.3 percent for Nuttall oak (*Q. nuttallii* Palmer). Germination and survival of swamp laurel oak (*Q. laurifolia* Michx.), willow oak (*Q. phellos* L.), and water oak (*Q. nigra* L.) ranked intermediate and averaged 21 percent. Nuttall oak seedlings averaged about 18.6±0.7 inches tall after two growing seasons, while shoot length of swamp laurel oak and water oak averaged 8.8±0.6 inches. Species rankings for growth of root-collar diameter tracked those for height growth. For a given species, logistic function models indicated that site factors associated with relative elevation in the flood plain strongly influenced seedling establishment and survival. Establishment and survival of all species responded positively to elevation. We summarize implications of our findings to afforestation and reforestation of alluvial flood plain sites within the context of site delineation and species assignments.

INTRODUCTION

Bottomland hardwood forests currently occupy about 29.8 million acres within alluvial flood plains of rivers and streams in the Southern United States (Hodges 1995). Regenerating bottomland hardwood stands classically involves natural regeneration methods (Hodges 1995). But more intensive management regimes are being instituted on alluvial flood plains as forest acreage declines and as consumers place greater demands on these forest resources. This shift to more intensive management appears in the increase in artificial regeneration activities on bottomland hardwood sites throughout the South. Enrichment planting in natural stands understocked with desirable reproduction and afforestation of marginal agricultural land are the primary practices spurring the expansion of artificial regeneration on alluvial flood plains. For example, about 447,000 acres of economically marginal agricultural land in Louisiana, Mississippi, and Arkansas are scheduled for afforestation by 2005 (Stanturf and others 1998).

Bottomland oak species (*Quercus* spp.) are favored for their commercially valuable wood and their desirable hard mast and, thus, are commonly used in afforestation and reforestation. Early research on oak plantation establishment in the Mississippi Alluvial Plain led to current direct seeding and seedling planting techniques (Kennedy 1993). Though these advances have provided sound procedures for establishing bottomland oak regeneration, plantation establishment on alluvial flood plain sites is still problematic. For example, oak seedlings often exhibit very slow growth that causes them to remain under herbaceous competition for several years before making significant gains in height increment (Kennedy 1993). Heavy herbaceous cover provides habitat for rodents that can destroy young plantations or retard seedling growth for several years by clipping shoots (Johnson 1981). Furthermore, the composite of site types typical of alluvial flood plains complicates the task of species assignments, often leading to deployment of inappropriate species on afforestation and reforestation sites.

Erosional and depositional processes in alluvial flood plains of the South can create heterogeneous site conditions over a relatively small area (Hodges and Switzer 1979, Putnam and others 1960). Several site types are recognized in alluvial flood plains, and these sites are delineated as topographic features or landforms. Fronts and ridges, which are the highest landforms in alluvial flood plains, experience infrequent flooding of short duration and are characterized by relatively coarse-textured, well-drained soils. Sloughs and swamps, the lowest landforms in flood plains, are frequently flooded for long durations and have heavily textured, very poorly drained soils. Flooding regime, soil texture, and drainage of flats are intermediate between those of ridges and sloughs (Hodges 1995).

Site factors, including moisture availability, flooding regime, and soil drainage, interact with the physiological functions of flood plain trees, resulting in species associations unique to each site type. For example, ridges are occupied by flood-intolerant species that require well-drained soils; e.g. American sycamore (*Platanus occidentalis* L.) and water oak (*Q. nigra* L.). Flood-tolerant species such as baldcypress [*Taxodium distichum* (L.) LC Rich.] and water tupelo (*Nyssa aquatica* L.) typically grow on the poorly drained soils of sloughs and swamps where they endure extended flooding (Hodges and Switzer 1979, Putnam and others 1960). Thus, topographic features in flood plains have various edaphic and hydrologic conditions manifested through vegetation associations. Field observations indicate bottomland oak species are stratified among sites in mature forests of alluvial flood plains (Tanner 1986). To

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

investigate the importance of seedling establishment on the distribution of bottomland oaks, we installed a plantation of five oak species along a topographical gradient in an alluvial flood plain. Our aim was to determine if microsite factors associated with flood plain relief influenced bottomland oak seedling establishment.

METHODS

Study Area

The study is located near the confluence of the Tombigbee and Alabama Rivers in Clarke County, AL (31°19' N., 87°51' W.) on an area previously abandoned as an American sycamore plantation. The surface of the field decreased in elevation from a ridge to a slough on about a 1-percent grade; i.e., there was a 4-foot decrease in elevation over 400 feet of surface. Soil cores were extracted along the elevational gradient on the study site to identify physical characteristics. An Urbo-Mantachie-Una soil complex predominated the site. Soil on the lowest portion of our study area (the slough or return channel) was typical of the Una series. Una is a poorly drained soil with very slow runoff and permeability. Una soils are classified as fine, mixed, active, acid, thermic Typic Epiaquept with a thin clay surface overlying a clay subsoil. Soil characteristic of intermediate positions on our study area belonged to the Urbo series. Urbo is somewhat poorly drained with slow runoff and very slow permeability. It is classified as fine, mixed, active, acid, thermic Vertic Epiaquept with a clay surface overlying a clay subsoil. The Mantachie series was typical of the highest portion of our study area and is typically found on high flats and low ridges. Mantachie is somewhat poorly drained with slow runoff and moderate permeability. This series is classified as fine-loamy, siliceous, active, acid, thermic Aeric Endoaquept with a fine sandy loam surface overlying a clay loam subsoil. All three soils on the study site experience annual flooding for brief (ridge and high flat) to long duration (low flat and return channel). Cover on the study area was primarily herbaceous species including sugar cane plume grass [*Erianthus giganteus* (Walter) Muhl.], panic grass (*Panicum rigidulum* Bosc ex Nees), beak rush [*Rhynchospora corniculata* (Lam.) A. Gray], and marsh mallow (*Hibiscus laevis* Allioni). We mowed the area in preparation for planting, but practiced no further weed control during the study.

Experimental Design

Five oak species were systematically direct seeded along the topographical gradient in April 1993. Overcup oak (*Q. lyrata* Walt.), Nuttall oak (*Q. nuttallii* Palmer), swamp laurel oak (*Q. laurifolia* Michx.), willow oak (*Q. phellos* L.), and water oak were selected for this study, because these species are native to the region and exhibit different site preferences in natural stands. Acorns were collected under at least five different parent trees growing in alluvial bottoms of east-central Mississippi and west-central Alabama. These acorns were float tested (except for overcup oak) to eliminate those damaged by insects, then they were stored in polyethylene bags under refrigeration until sowing (Bonner and Vozzo 1987). Three replications of plots were established as a grid along the topographical gradient. In each plot, 70 rows were delineated at 6-foot intervals perpendicular to the slope. In each row, five planting spots were flagged 2 feet apart, and two acorns for each species were seeded at a randomly chosen spot in each row. Thus, 420 acorns were seeded 3 to 4 inches deep for each species along the topographical gradient.

Table 1—Model coefficients[a] for predicting seedling establishment for direct seeded acorns in an alluvial floodplain, Alabama

Species	b_1	b_2	b_3
Overcup oak	1.0000	2.9196	-0.4088
Nuttall oak	0.5286	0.7392	-0.6051
Swamp laurel oak	0.3183	1.5895	-0.8304
Willow oak	1.0000	3.2266	-0.8113
Water oak	0.4176	9.1738	-4.5961

[a] Logistic model for establishment = $b_1/(1+e^n)$, where $n = (b_2 + b_3 * \text{elevation})$.

Seedling survival, height, and diameter data were collected after the first 2 growing seasons for each of the 420 acorns sown for each species. Also, relative elevation at each planting spot was measured with a transit and leveling rod in an attempt to relate seedling survival and establishment success to flood plain relief. Analysis of variance according to a completely random design tested for a species effect on survival and height growth ($\alpha = 0.05$). A logistic function modeled seedling establishment from direct-seeded acorns and planted seedling survival along the topographical gradient (Hamilton 1986, Monserud 1976). Model coefficients for each species and stock type are presented in table 1.

RESULTS AND DISCUSSION

Establishment and Growth

Two years after sowing, seedling establishment from direct-seeded acorns ranged from 33 percent for Nuttall oak to 12 percent for overcup oak ($P < 0.0001$) (table 2). Establishment rates for swamp laurel oak, willow oak, and water oak were intermediate and averaged about 21 percent following the second growing season. Nuttall oak germinants were the tallest after two growing seasons, with an average height of 18.7 inches ($P < 0.0001$) (table 2). Swamp laurel oak and water oak germinants grew the least with an average shoot height < 10 inches after two growing seasons. Overcup and willow oak germinants grew more than 4 inches taller than those of swamp laurel oak and water oak. Results for root-collar diameter growth were similar to those for height growth (table 2). Nuttall oak seedlings developed the largest root-collar diameters, followed by overcup oak and willow oak, then swamp laurel oak and water oak.

In this study, direct-seeded Nuttall oak showed the highest germination rate and also the greatest height and diameter growth. The superior germination and early height growth of this species is consistent with other research on direct-seeded bottomland oaks and undoubtedly leads to its popularity in direct seeding operations (Johnson 1981). Direct seeding Nuttall oak has yielded first-year establishment rates as high as 55 to 71 percent in the Mississippi Alluvial Plain, but 35 percent is a reasonable estimate of the establishment rate for direct-seeded Nuttall oak (Johnson and Krinard 1985, Kennedy 1993, Miwa and others 1993). In contrast, we observed poor establishment

Table 2—First- and second-year survival, seedling height, and root-collar diameter of five bottomland oak species direct seeded along a topographic gradient in an alluvial floodplain, Alabama[a]

Species	Survival		Height		Diameter	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
	- - - - - - - percent - - - - - - - -		*- - - - - - - - inches - - - - - - - -*		*- - - - - - - - 0.1 inch - - - - - - -*	
Overcup oak	43.5 ± 2.4 c	12.4 ± 1.6 c	6.8 ± 0.24 b	15.9 ± 1.02 b	0.83 ± 0.02 b	1.77 ± 0.11 b
Nuttall oak	58.8 ± 2.4 a	33.0 ± 2.3 a	9.4 ± 0.31 a	18.7 ± 0.71 a	1.29 ± 0.03 a	2.36 ± 0.11 a
Swamp laurel oak	47.8 ± 2.4 bc	18.7 ± 1.9 b	5.3 ± 0.19 c	9.7 ± 0.63 c	0.83 ± 0.02 b	1.29 ± 0.06 c
Willow oak	58.8 ± 2.4 a	22.0 ± 2.0 b	6.3 ± 0.19 b	14.2 ± 0.83 b	0.75 ± 0.02 c	1.42 ± 0.07 b
Water oak	52.4 ± 2.4 ab	22.2 ± 2.0 b	4.5 ± 0.16 d	7.9 ± 0.55 c	0.63 ± 0.02 d	0.98 ± 0.05 c

[a] Values presented are means ± standard error of the mean. Entries in a column followed by the same letter do not differ at the 0.05 probability level.

for direct-seeded overcup oak. A twofold to threefold increase in sowing rate would have been required to establish an overcup oak seedling density similar to that observed for Nuttall oak. Low acorn viability may partially explain the poor establishment rate for overcup oak. Prior to direct seeding, a standard float test separated sound acorns from insect-damaged acorns. However, this test is not appropriate for overcup oak acorns, which have a corky layer around the cotyledons that causes the seed to float. Thus, we were not able to remove insect-damaged overcup oak acorns from the lot.

In this experiment, newly established oak seedlings showed slow juvenile growth rates in comparison to other shade-intolerant bottomland species. Typically they favor root growth over shoot growth in high light environments and defer significant height growth until several years after establishment (Gardiner and Hodges 1998, Hodges and Gardiner 1993, Wittwer 1991). Swamp laurel oak and water oak showed the poorest height growth of new germinants in this study. This characteristic may be detrimental to these species on bottomland sites with rank competition or on sites with frequent or extended floodwater inundations.

Influence of Topography on Seedling Establishment

The primary objective of this study was to determine if seedling establishment or survival was controlled by factors associated with flood plain topography. Seedling establishment from direct-seeded acorns of bottomland oaks appeared to vary with elevation (fig. 1). All species generally exhibited a positive establishment slope along the topographic gradient; i.e., seedling establishment increased with increasing elevation (fig. 1). But oak species had differing establishment patterns along the elevational gradient. For example, Nuttall oak showed the best predicted establishment (about 20 percent) on the lowest end of the study area (fig. 1). For this species, predicted establishment increased about 28 percent to a maximum rate of 45 percent on the highest portion of the study area. Seedling establishment from overcup oak and swamp laurel oak acorns appeared least responsive to the gradient, increasing only 15 and 22 percent, respectively, with elevation. Establishment of seedlings from direct-seeded water and willow oak acorns was highly responsive to the gradient. For water oak, virtually no establishment was recorded on the lowest quarter of the plantation. But, establishment for this species quickly increased above that point to a maximum near 41 percent. Predicted establishment of reproduction from willow oak acorns increased from about 4 percent on the lowest end of the study area to > 54 percent on the highest end (fig. 1). It appears that factors associated with topographical gradient greatly influenced success of seedling establishment from direct-seeded water and willow oak acorns.

Though edaphic and hydrologic factors drive productivity of bottomland hardwoods (Baker and Broadfoot 1979, Broadfoot 1976), we are aware of only one other study which has attempted to relate germination and establishment of direct-seeded bottomland oaks to edaphic or hydrologic factors in the field. Miwa and others (1993), who studied bottomland oak afforestation methods in the Mississippi Alluvial Valley, were unable to detect effects of three different soil series on first-year germination and growth of four bottomland oak species. This finding was consistent through 5 years after plantation establishment (Ozalp and others 1998). They attributed this lack of a soil series effect on oak germination and survival to the absence of seasonal flooding during the 5-year study period. Their field conditions were in sharp contrast to those on our study site, which received spring flooding each of the 2 sample years.

CONCLUSIONS

In an alluvial flood plain, establishment success and growth of five bottomland oak species varied by species. Of the species we examined, direct-seeded Nuttall oak showed superior establishment and growth. Overcup oak showed poor establishment success across the entire study area, but height and diameter growth of this species exceeded that of swamp laurel oak and water oak. Interestingly, for a given species, microsite factors associated to flood plain topography influenced topography. This finding is particularly noteworthy as there was only a 1-percent grade across the study area.

This research illustrates that microsite factors drive bottomland oak seedling establishment on alluvial flood plains, emphasizing important considerations for artificial regeneration of bottomland hardwood sites. First, accurate identification of site conditions prior to afforestation or reforestation is absolutely critical. Sensible species assignments for regeneration projects can be made only after identifying

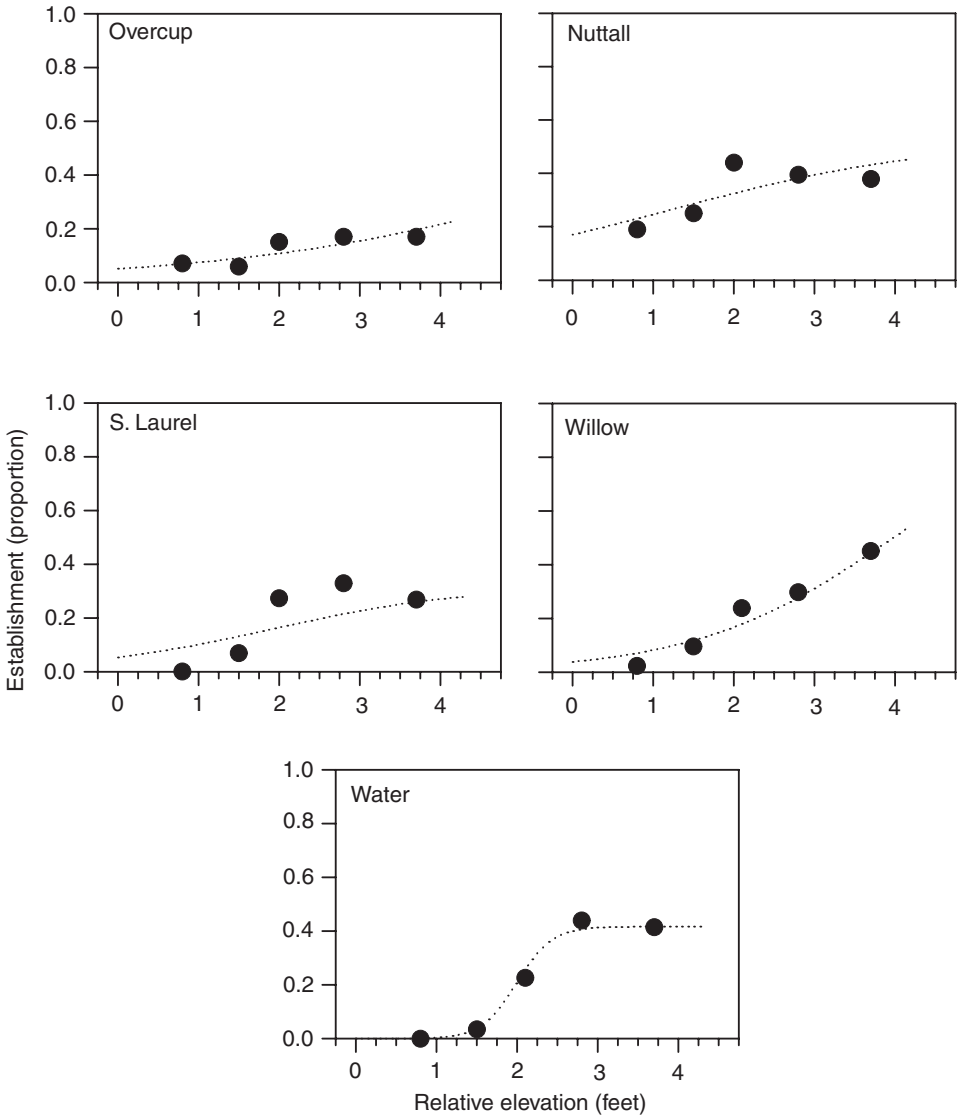

Figure 1—Establishment proportions as predicted with a logistic function 2 years after direct seeding along an elevational gradient on an alluvial flood plain near the confluence of the Alabama and Tombigbee Rivers, AL. Data points represent the mean establishment observed at elevational quintiles on the gradient. These points are projected for reference only and were not the data points used to model predicted establishment.

and delineating site conditions on the ground. Second, bottomland sites should be regenerated with species mixtures to improve establishment success. Even after identifying site conditions and assigning appropriate species, uncontrollable problems of plant phenology or weather may reduce establishment success of certain species. Next, species mixtures should be intergraded along margins of topographic features in alluvial flood plains. These features are often subtle, leading to a gradual shifting of site conditions and precluding assignment of absolute boundaries between site types. Finally, planting or sowing density should match site conditions that may potentially affect establishment. For example, oak establishment was difficult on the lowest portion of our study site, probably due to poor soil drainage or flooding intensity or duration. Anticipating such problems, the regeneration forester can modify sowing or planting rates accordingly.

ACKNOWLEDGMENTS

This research was initiated while ESG and JDH were at the Department of Forestry, Mississippi State University; and TCF was with Kimberly-Clark. A significant portion of this research was funded by Kimberly-Clark in Saraland, AL. Several people, including Parker Day, Paul Havard, Richard Keim, Masato Miwa, Mitch White, and Greg Williams, assisted with plantation establishment and measurement. Jeff Goelz assisted with the logistic modeling procedures.

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MONITORING AND ASSESSMENT OF TREE ESTABLISHMENT IN THE WETLAND RESERVE PROGRAM IN THE LOWER MISSISSIPPI ALLUVIAL PLAIN

Callie Jo Schweitzer[1]

POSTER SUMMARY

Reforestation of marginally productive agricultural fields has been aided by cost-share programs, including the Wetland Reserve Program (WRP), administered by the U.S. Department of Agriculture, Natural Resources Conservation Service. Mississippi was chosen as a pilot State charged with implementing WRP in 1992. Reforestation efforts were emphasized under WRP. The introduction of hard mast species was a main goal. In particular, the hard mast species highlighted were oaks. Oak species introduced on these tracts included Nuttall oak (*Quercus nuttallii* Palmer), willow oak (*Q. phellos* L.), water oak (*Q. nigra* L.), cherrybark oak (*Q. pagoda* Raf.), and overcup oak (*Q. lyrata* Walt.). Sawtooth oak (*Q. accuminata* Carruth.) was planted along with Nuttall oak on one tract, although sawtooth oak was not on the WRP approved species list. However, no sawtooth oak seedlings survived. Seedlings [oaks, green ash (*Fraxinus pennsylvanica* Marsh.), water hickory (*Carya aquatica* Michx.), and baldcypress (*Taxodium distichum* L.)] were planted on a 12- by 12-foot spacing at a rate of 302 trees per acre. Direct seeding (sowing) was at a rate of 1,210 acorns per acre on a 12- by 3-foot spacing at a depth of 2 to 4 inches. Both machine and hand planting were used. No postreforestation weed control was used.

A survey of tree species established on 1992 WRP contracts was conducted in late fall of 1996. The average growing time of the planted seedlings or acorn germinants was 31 months. Forty-seven 0.01-acre plots were systematically placed in each tract of land enrolled in WRP in 1992. All trees listed on the Mississippi WRP approved species list were counted and identified by species. The successful establishment criterion modified for Mississippi WRP was 100 trees per acre.

Out of the 9,387.7 acres reforested, 8,800.4 acres were direct seeded with different species of oaks, and 587.2 acres were planted with 1-0 stock bare-root seedlings of oak and other species. At the time of the survey, 137.0 acres of the total 587.2 acres that were planted with seedlings had an average of 100 trees per acre (23 percent), and 739 acres of the total 8,800.4 acres that were direct seeded had an average of 100 trees per acre (8.4 percent). Fifteen percent (7/47) of all tracts were successfully reforested.

For both oak and all tree species, seedling survival was significantly higher than acorn germinant survival. Acorn-germinant survival assessments showed that acorns sown in January had significantly greater survival than those sown in March. Survival of planted seedlings did not differ by month planted. Seedling planting occurred either in January or March.

It was not possible to determine the exact reason for such low survival rates. Our limited experience in restoring forested wetlands has demonstrated that restoration is often unpredictable, of variable or unknown cost, and of uncertain stability. Reforestation is a long-term undertaking, a continuous process. We need to use up-to-date information in order to develop reforestation plans that best meet the site needs, thus increasing our chances of success.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

PARTIAL CUTTING AND ESTABLISHMENT OF ARTIFICIAL NUTTALL OAK REGENERATION IN THE MISSISSIPPI ALLUVIAL PLAIN

Benjamin P. Ware and Emile S. Gardiner[1]

Abstract—In the fall of 1998, we harvested a mixed bottomland hardwood stand in Sharkey County, MS, to establish two replicates of three residual stocking levels (0, 25, and 50 percent). We compared the various stand densities for suitability in establishment and growth of artificial oak regeneration. Following the overstory harvest, treatment plots received chain saw site preparation, then in March 1999 1-0 Nuttall oak (*Quercus nuttallii* Palmer) seedlings were hand-planted across the study site. To examine the efficacy of competition control on improving seedling survival and growth, half of the seedlings received a spot application of a broad-spectrum herbicide. Third-year survival of planted seedlings averaged 77 percent across the site, providing > 570 stems/ha. Third-year measurements on surviving seedlings indicated more vigorous growth under 0-percent residual stand stocking where seedlings developed to a mean height of 152±9 cm (mean ± standard error) and a mean root-collar diameter of 17.8±1.4 mm. Height and root-collar diameter of seedlings planted beneath partial overstories did not differ by overwood stocking level and averaged 95±8 cm and 12.3±0.9 mm, respectively. Competition control did not improve seedling survival or height growth but slightly increased root-collar diameter 3 years after treatment. However, seedlings receiving competition control were 44 percent more likely to be free to grow than seedlings that did not receive competition control. We present silvicultural implications of these results for bottomland oak regeneration.

INTRODUCTION

Adequate advance oak reproduction on bottomland sites has long been seen as problematic (Chambers and Henkel 1989, Lockhart and others 2000, Nix and Cox 1987). Acknowledging this problem, Johnson (1979) predicted a bleak long-term outlook under current regeneration practices on bottomland sites. Interestingly, some oak reproduction is usually present in the understory of mature oak stands, but it is usually too sparse, poorly distributed, or, more commonly, too small to release (Sander 1972). Any of these conditions often lead to a significantly smaller component of oak in the stand that develops after harvest. New practices demonstrate potential for increasing the size and vigor of natural oak reproduction (Lockhart and others 2000), but reliable techniques are needed for artificially regenerating bottomland oak stands.

Johnson and others (1986) demonstrated that controlling undesirable vegetation, increasing light levels on the forest floor by removing a portion of the canopy, and seedling underplanting provide a promising practice for establishing advance northern red oak (*Quercus rubra* L.) reproduction in the Missouri Ozarks. Earlier studies in bottomlands indicate that similar practices may be useful for establishing bottomland oaks (Chambers and Henkel 1989, Gardiner and Yeiser 1999). However, partial cutting operations and underplanting to establish advance oak reproduction on bottomland hardwood sites have not been broadly examined, and sufficient knowledge to reliably prescribe these practices is lacking. Specifically, guidelines for intensity of partial cutting and competition-control techniques do not exist for bottomland oak underplanting practices, and underplanting partially cut stands has not been directly compared with the clearcut method of regeneration. The objectives of this study were to examine (1) the influence of a partial overstory on the establishment and growth of Nuttall oak (*Q. nuttallii* Palmer) seedlings and (2) the importance of woody competition control for establishment and growth of Nuttall oak seedlings beneath a partial canopy. In this manuscript we present third-year results from the study.

METHODS

Study Site

The study was conducted in Sharkey County, MS, on a 16th-section property under the management of the Mississippi Forestry Commission. The site (90°43'W. longitude, 32°58'N. latitude) is approximately 10 km east of Anguilla, MS, and 3 km north of the Delta National Forest. Soils on this site are Alligator series (very fine, smectitic, Thermic Dystraquerts) and Dowling series (very fine, smectitic, Thermic Endoaquepts). Annual rainfall in Sharkey County averages 1320 mm, and the mean annual temperature is 17.8 °C (January mean 7.5 °C, July mean 27.8 °C) (Scott and Carter 1962). Overstory and midstory species prevalent on the site included willow oak (*Q. phellos* L.), Nuttall oak, overcup oak (*Q. lyrata* Walt.), American snowbell (*Styrax americana* Lam.), deciduous holly (*Ilex decidua* Walt.), cedar elm (*Ulmus crassifolia* Nutt.), and American elm (*U. americana* L.). Prior to treatment, trees on the site had an average diameter at breast height (d.b.h.) of 44.2 cm, and basal area averaged 25.5 m^2/ha.

Experimental Design

The study was designed to test the effect of two factors, stand-stocking level and competition control, on survival and growth of artificial Nuttall oak regeneration. We examined three target levels of stand stocking (0, 25, and 50 percent) and two levels of competition control (none and single-spot application of a broad-spectrum herbicide).

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

Thus, we established six treatment combinations according to a split-plot design, assigning stand-stocking level to whole plots and competition control to split plots.

The site was divided into two blocks (based on soil type) in which three 1.7-ha whole plots were delineated. Within each block, whole plot treatments were assigned according to a randomized block design. Assigned stocking levels were marked in each plot following bottomland hardwood stocking equations outlined in Goelz (1995). In fall 1998, plots were harvested to their target stocking level by a conventional chain saw and skidder logging operation. After logging, each plot received chain saw site preparation to sever at groundline all midstory stems with a d.b.h. $\geq$ 2.5 cm and to reduce the height of logging slash piles. After harvest, plots targeted to receive 25-percent residual stocking actually had a residual overstory of 39 trees/ha, an average d.b.h. of 48.8 cm, an average basal area of 7.6 m^2/ha, and a residual stand stocking of 26 percent. Plots targeted to receive 50-percent residual stocking actually had a residual overstory of 89 trees/ha, an average d.b.h. of 46.8 cm, an average basal area of 15.37 m^2/ha, and a residual stand stocking of 53 percent.

Prior to planting, each whole plot was split and randomly assigned a competition control level. In March 1999, a contracted planting crew hand-planted 100 bareroot Nuttall oak seedlings (1-0) on 3.6- by 3.6-m spacing in each split plot. In May 1999, seedlings assigned competition control received a directed application of Roundup Ultra™ (10-percent solution) within a 1.5-m diameter circle centered over the seedling. Oak seedlings were covered with a PVC pipe during herbicide application to prevent herbicide contact with the seedling. Height and root-collar diameter of all planted seedlings in each measurement plot were measured immediately after planting and at the end of the third growing season.

Statistical Analyses

We analyzed survival, height growth, and root-collar diameter growth of planted seedlings according to a split-plot design (SAS Institute Inc., Cary, NC). Table 1 presents the analysis of variance (ANOVA) sketch for the randomized block design with split plots. All tests were conducted at an $\alpha = 0.05$.

Table 1—Analysis of variance sketch for a randomized block design with split plots used for analysis of response variable plot means

Source	Degrees of freedom[a]
Total	rab-1 = 11
Block	(r-1) = 1
Stocking	(a-1) = 2
Error (stocking)	(r-1)(a-1) = 2
Competition control	(b-1) = 1
Stocking x competition control	(a-1)(b-1) = 2
Error (stocking x competition control)	a(r-1)(b-1) = 4

[a] r = two blocks; a = three residual stand stocking levels; b = two competition control levels.

RESULTS

Seedling Response to Stand-Stocking Level

Nuttall oak seedling stock averaged about 70 cm tall at planting (table 2). Three years after planting, we observed the most vigorous height growth on seedlings established under the 0-percent stand-stocking level. These seedlings grew 120 percent relative to their initial planting height (table 2). Height growth of seedlings established under the 25-percent and 50-percent stand-stocking levels both showed an average growth of 39 percent relative to their initial height. The reduced rate of height growth on seedlings beneath partial overstories yielded seedlings that were 37 percent smaller than those in the open (table 2).

Based on differences in the mean height of seedlings, we expected a shift in the distribution of seedling height classes among the three residual stand-stocking levels. Figure 1 illustrates the more rapid advancement of seedlings into higher size classes when they are planted in the open. In contrast, relatively few seedlings established beneath a residual canopy developed into the largest size classes. When established beneath the 50-percent residual stand stocking, only 6 percent of the surviving seedlings, amounting to 35/ha, grew into a size class 150 cm tall or greater. Twenty percent of the surviving seedlings established under 25-percent stocking, or 115/ha, grew into a size class 150 cm tall or greater. This growth is in contrast to 52 percent, or 289 seedlings/ha, that grew into these size classes when planted in the open.

The mean root-collar diameter of the 1-0 Nuttall oak planting stock was about 8.7 mm (table 3). Third-year root-collar measurements agreed with height measurements: the most vigorous growth occurred on seedlings established under a 0-percent stocking level. These seedlings exhibited 107-percent growth relative to their root-collar diameter at planting. Root-collar diameter of seedlings established under the 25-percent and 50-percent stand-stocking levels both averaged 48-percent growth relative to their initial size. Seedlings under a canopy developed an average root-

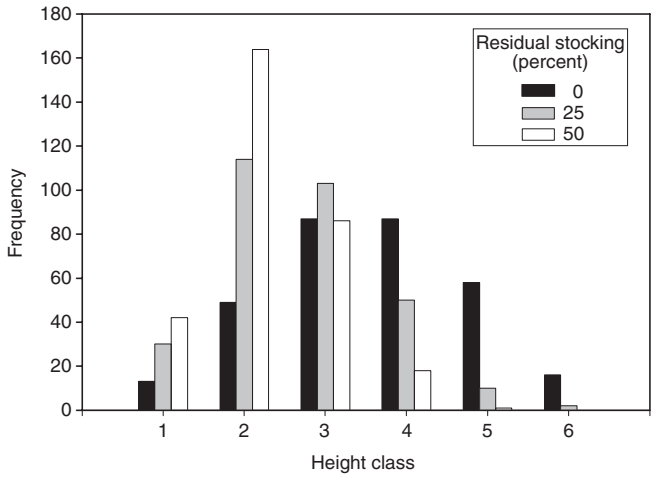

Figure 1—Height distribution of surviving Nuttall oak seedlings three growing seasons after planting under three residual stand-stocking levels on a bottomland site in Sharkey County, MS.

Table 2—Initial height, third-year height, and relative growth (mean ± standard error) of Nuttall oak seedlings underplanted in the Mississippi Alluvial Plain, Sharkey County, MS

Treatment effect[a]	Initial	Final	Growth
	- - - - - - - - - *cm* - - - - - - - - -		*percent*
Stocking			
0%	70.4 ± 2.3 a	151.6 ± 8.8 a	120.7 ± 0.2 a
25%	70.1 ± 1.0 a	104.3 ± 8.5 b	49.0 ± 0.1 b
50%	68.5 ± 0.8 a	85.8 ± 8.5 b	29.9 ± 0.1 b
P-value	0.6373	0.0002	0.0078
Competition control			
Spot application	71.2 ± 0.9 a	114.7 ± 14.7 a	61.9 ± 0.2 a
None	68.1 ± 1.1 a	113.1 ± 13.4 a	71.2 ± 0.2 a
P-value	0.1542	0.7701	0.3077

[a] For each treatment effect, means followed by the same letter are not different at $\alpha = 0.05$.

Table 3—Initial root-collar diameter, third-year root-collar diameter, and relative growth (mean ± standard error) of Nuttall oak seedlings underplanted in the Mississippi Alluvial Plain, Sharkey County, MS

Treatment effect[a]	Initial	Final	Growth
	- - - - - - - - - *mm* - - - - - - - - -		*percent*
Stocking			
0%	9.0 ± 0.2 a	17.8 ± 1.4 a	107.6 ± 0.2 a
25%	8.4 ± 0.1 a	13.3 ± 1.1 b	61.0 ± 0.2 b
50%	8.7 ± 0.2 a	11.3 ± 0.7 b	36.3 ± 0.1 b
P-value	0.1784	0.0394	0.0354
Competition control			
Spot application	8.8 ± 0.2 a	15.0 ± 1.5 a	76.7 ± 0.2 a
None	8.6 ± 0.1 a	13.2 ± 1.4 b	59.9 ± 0.2 a
P-value	0.1701	0.0466	0.2131

[a] For each treatment effect, means followed by the same letter are not different at $\alpha = 0.05$.

collar diameter 31 percent smaller than those in the open (table 3).

Third-year survival of planted seedlings averaged 77 percent, resulting in > 570 stems/ha for all overstory treatments (table 4). Residual stand-stocking level did not influence seedling survival. Furthermore, stand-stocking level did not affect the seedlings' ability to achieve free-to-grow status (table 5). Across the study site, 49 percent of all surviving seedlings were free to grow 3 years after establishment.

Seedling Response to Competition Control

A single application of a broad-spectrum herbicide did not improve seedling growth or survival in this study (tables 2, 3, and 4). Height after 3 years of growth for treated and untreated seedlings both averaged 114 cm (table 2). Similarly, mean root-collar diameters between treated and untreated seedlings both averaged 14.0 mm (table 3). Seedlings exhibited 66-percent height growth and 68-percent root-collar diameter growth relative to the initial planting stock.

Nuttall oak seedlings that were not overtopped by competing vegetation were assigned a free-to-grow status during the third-year measurements. Competition control may have had an effect on the reduction of competition, as the analysis shows a significant amount (58 percent, or 333 stems/ha) of the surviving treated seedlings were free to grow after the third year (table 5). After three growing seasons, seedlings receiving competition control were 44

Table 4—Third-year survival of Nuttall oak seedlings underplanted in the Mississippi Alluvial Plain, Sharkey County, MS

Treatment effect[a]	
	percent
Stocking	
0%	77.5 ± 0.1 a
25%	77.5 ± 0.1 a
50%	77.8 ± 0.1 a
P-value	0.9990
Competition control	
Spot application	77.0 ± 0.1 a
None	78.2 ± 0.1 a
P-value	0.8205

[a] For each treatment effect, means followed by the same letter are not different at $\alpha = 0.05$.

Table 5—Percent (mean ± standard error) of Nuttall oak seedlings that were free to grow 3 years after underplanting in the Mississippi Alluvial Plain, Sharkey County, MS

Treatment effect[a]	Free to grow
	percent
Stocking	
0%	52.7 ± 0.1 a
25%	49.8 ± 0.0 a
50%	45.3 ± 0.1 a
P-value	0.1939
Competition control	
Spot application	58.1 ± 0.1 a
None	40.4 ± 0.0 b
P-value	0.0323

[a] For each treatment effect, means followed by the same letter are not different at $\alpha = 0.05$.

percent more likely to be free to grow than the untreated seedlings.

DISCUSSION

Light availability may be a primary factor restricting early development of oak reproduction in mature bottomland hardwood stands (Lockhart and others 2000). This influence generally relates to stand structure, as the heavy midstory layer of many mature bottomland hardwood stands restricts light availability in the understory (Jenkins and Chambers 1989, Lockhart and others 2000). Additionally, seedlings of most bottomland oak species are shade intolerant, but oak reproduction is often out-competed by faster growing intolerant species under full light availability (Hodges and Gardiner 1993). Applying a partial harvest to prepare a bottomland hardwood stand for regeneration may increase understory light availability to oak reproduction without completely releasing competitors to full sunlight. Accordingly, we question if an optimal level of partial cutting will invigorate the growth of oak reproduction and minimize the response by competition.

Few studies have examined the response of artificial oak reproduction to a range of canopy or stand structures in bottomland hardwood forests. Chambers and Henkel (1989) have reported the most comprehensive study of oak seedling response to various levels of overstory removal in bottomland stands to date. They observed 77-percent survival of underplanted Nuttall oak seedlings 2 years after establishment beneath six different levels of overstory removal, and survival did not differ by the level of overstory removal (Chambers and Henkel 1989). Survival of Nuttall oak in our study, consistent with the findings of Chambers and Henkel (1989), confirms that light availability does not greatly influence early survival of underplanted Nuttall oak seedlings. Nix and others (1985) reported similar results for cherrybark oak (*Q. pagoda* Raf.) planted beneath a shelterwood and a clearcut in a hardwood bottom of the Wateree River, SC.

In contrast to survival, the presence of a partial overstory impacted Nuttall oak seedling height and diameter growth. Greatest growth occurred where the overstory was completely removed, but we did not detect growth differences between seedlings established under the two levels of residual stand stocking. Similarly, Nix and others (1985) observed that 2-0 cherrybark oak seedlings showed relatively greater growth 3 years after establishment in a clearcut vs. a shelterwood. Growth of underplanted Nuttall oak seedlings relative to degree of canopy removal appeared inconclusive for Chambers and Henkel (1989). However, though the presence of the overwood reduced height and diameter growth of Nuttall oak, underplanted seedlings did maintain positive shoot growth during the 3-year study.

Two additional thoughts should be noted for seedling growth. First, annual precipitation in at least two of the three growing seasons in this study was well below the annual average. If competition for soil moisture would be greatest where overstory trees are retained, this competition in addition to the relatively dry growing seasons may have reduced growth of underplanted seedlings more than expected. Second, we would expect the growth response by existing Nuttall oak seedlings in the understory to differ from that of underplanted seedlings. This, we speculate, would be due to differences in root architecture and seedling acclimation to the forest understory.

Directed application of woody competition control can potentially favor desirable species in regenerating bottomland hardwood stands. However, improper application of herbicides in hardwood stands creates the potential to damage desirable stems (Nix and others 1985). Survival and height growth of seedlings in this study did not respond to the competition control treatment. We did detect a slight increase in the root-collar diameter of seedlings receiving competition control, and these findings agree with those reported for cherrybark oak receiving similar competition control (Nix and others 1985). Our finding is also consistent with Miller (1993), who reported that competition control generally initiates a relatively greater response in seedling diameter growth than height growth. In our study, a single-spot application of a broad-spectrum herbicide appeared to decrease the vigor of competing vegetation enough to allow oak seedlings freedom to grow. This result will potentially influence future stand development. Schmeckpeper and others (1987) also reported more free-to-grow stems after glyphosate treatment of Japanese honeysuckle in a bottomland hardwood stand.

CONCLUSIONS

Artificial Nuttall oak regeneration was successfully established under a wide range of residual stand-stocking levels in a bottomland hardwood stand of the Mississippi Alluvial Plain. Seedlings established in clearcuts showed the most vigorous height and diameter growth, while establishment beneath a partial overstory reduced the rate of height and diameter growth over the 3-year study. Nevertheless, seedlings beneath partial canopies maintained positive growth and should be in a condition to respond positively to overstory removal. Competition control in this study had no effect on the growth of Nuttall oak seedlings, but did reduce competing vegetation such that a greater percentage of oak seedlings were able to attain a free-to-grow status. It remains to be seen if this will influence future stand development.

Establishment and growth of Nuttall oak seedlings observed in our partially cut stands provide promise for development of alternative regeneration practices that temporarily maintain vertical structure in bottomland hardwood forests.

ACKNOWLEDGMENT

This research was conducted in cooperation with the Mississippi Forestry Commission. The authors express their appreciation to commission personnel who assisted with design and installation of the experiment, particularly Bobby Edwards, Brant Godbold, and Robin Rouse.

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RADIAL GROWTH OF NINE SELECTED 18-YEAR-OLD BALDCYPRESS PROVENANCES UNDER PROLONGED DROUGHT

P. Joy Young and Jim L. Chambers[1]

INTRODUCTION

Coastal and bottomland restoration have prompted an interest in species that tolerate wetland and/or saline conditions. It has been suggested that provenance tests may be used to explore a species' response to global climate change (Matyas 1994). Baldcypress, [*Taxodium distichum* (L.) Rich], a canopy dominant in the lower Atlantic and Gulf coast plains, has a broad distribution. Although the wide range suggests a large degree of genetic variability, no studies have explored the genetic variation in radial growth response to drought.

OBJECTIVES

The purpose of this study was to examine how radial growth of provenances may differ in response to long-term drought.

METHODS

In January 1999, we installed dendrometer bands in an 18-year-old baldcypress plantation, composed of 9 provenances from the Mississippi Alluvial Valley. Dendrometer bands were placed on one tree in each family row in each block, for a total of 280 trees. Changes in circumference were recorded weekly. Growth measurements were converted to basal area for comparisons.

RESULTS AND DISCUSSION

There were significant differences for weekly changes in basal area within each provenance across the 4 years of measurement. Only weekly growth at the beginning and end of the growing season were similar among years. Among provenances, cumulative basal area increases differed in 1999 and 2001, years of normal rainfall. However, growth for all provenances was similar in low rainfall years 2000 and 2002. Despite normal rainfall in 2001, onset of growth was delayed in 2002, and total growth did not reach pre-drought levels. Prolonged drought appears to continue to negatively impact radial growth even after rainfall returns to normal levels.

ACKNOWLEDGMENTS

We thank Bob Keeland, Karen Velupillai, Andrew Gross, Erika Stelzer, and Luben Dimov for their help with fieldwork. This research was funded by the Gilbert Foundation.

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Citation for proceedings: Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 594 p.

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Connor, Kristina F., ed. 2004. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 600 p.

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