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18TH CENTRAL HARDWOOD FOREST CONFERENCE

Proceedings of a Conference held at
West Virginia University
Morgantown, West Virginia
March 26-28, 2012

Edited by:
Gary W. Miller, U.S. Forest Service
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Sponsored by:
West Virginia University Division of Forestry and Natural Resources
U.S. Forest Service, Northern Research Station

FOREWORD

The Central Hardwood Forest Conference is a series of biennial meetings dedicated to the sustainability and improvement of Central Hardwood forest ecosystems. The objective of the conference is to bring together forest managers and scientists to discuss research and issues concerning the ecology and management of forests in the Central Hardwood region. The conference has been hosted by different institutes across the region. The18th Central Hardwood Forest Conference was hosted by the Division of Forestry and Natural Resources of West Virginia University, and the Northern Research Station of the U.S. Forest Service. The conference includes presentations pertaining to biofuels and bioenergy, forest biometrics, forest ecology and physiology, forest economics, forest health including invasive species, forest soils and hydrology, geographic information systems, harvesting and utilization, silviculture, and wildlife management. The conference consisted of 54 oral presentations, resulting in 44 papers and 10 presentation abstracts as well as 31 poster presentations and associated abstracts published herein.

The 19th Central Hardwood Forest Conference (2014) will be hosted by Southern Illinois University and the Northern Research Station; and the 20th Central Hardwood Forest Conference (2016) has been proposed to be hosted by The Pennsylvania State University and the Northern Research Station.

STEERING COMMITTEE

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REVIEW PROCEDURES

A double-blind review process was used in reviewing manuscripts for oral presentations. Each manuscript was assigned to one of the subject matter reviewers and peer-reviewed by at least two professionals. Reviews were returned to authors to revise their manuscripts. Revised manuscripts were then submitted to the Northern Research Station, U.S. Forest Service for final editing and publishing. The conference editorial committee returned some of the manuscripts to the authors as being more appropriate for other outlets.

ACKNOWLEDGMENTS

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HISTORY OF THE CENTRAL HARDWOOD FOREST CONFERENCE

This Conference is the 18th in a series of biennial meetings that have been hosted by numerous universities and USDA Forest Service Research Stations in the Central Hardwood Forest Region including:

1976 Southern Illinois University
1978 Purdue University
1980 University of Missouri
1982 University of Kentucky
1985 University of Illinois
1987 University of Tennessee
1989 Southern Illinois University and the North Central Forest Experiment Station
1991 Pennsylvania State University and the Northeastern Forest Experiment Station
1993 Purdue University and the North Central Forest Experiment Station
1995 Northeastern Forest Experiment Station and West Virginia University
1997 University of Missouri and the North Central Forest Experiment Station
1999 University of Kentucky and the Southern Research Station
2002 University of Illinois, Urbana-Champaign and the North Central Research Station
2004 Ohio State University, Wooster and the Northeastern Research Station
2006 University of Tennessee, Knoxville and the Southern Research Station
2008 Purdue University and the Northern Research Station
2010 University of Kentucky and the Northern Research Station

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KEYNOTE PRESENTATIONS

INITIAL LANDSCAPE CHANGES ASSOCIATED WITH MARCELLUS SHALE DEVELOPMENT—IMPLICATIONS FOR FORESTS AND WILDLIFE

Margaret Brittingham, Patrick Drohan, and Joseph Bishop[1]

Marcellus shale development is occurring rapidly across Pennsylvania. We conducted a geographic information system (GIS) analysis using available Pennsylvania Department of Environmental Protection permit data, before and after photos, ground-truthing, and field measurements to describe landscape change within the first 3 years of active Marcellus exploration and development. The number of permits and wells drilled increased exponentially. More than 85 percent of drilling pads and wells are going into private land. Between 45 and 62 percent of the wells are going into farmland with the highest numbers in the northeast and southwest parts of the state. Between 30 and 54 percent of the wells are in forest lands. Of those, 23 percent are being placed in core forest (forest > 100 m from a pre-existing road or edge). These pads are a particular concern because of their potential to fragment forests as roads, pipelines, and other infrastructure are built. Mean drilling pad size is 1 ha with a range from 0.1 to 20 ha, and pads are typically covered with a stone surface. Sixteen percent of pads have undergone some type of reclamation that reduced pad size and local disturbance by over half. However, most reclamation is to grassy cover and not back to forest habitat. There is a trend toward more wells being built per pad, but currently more than 75 percent of pads have only one or two wells. Whether companies return to these pads in future years to add wells or build more pads in other locations will influence further landscape change. If rates and patterns of development continue in a similar manner, core forest habitat is at risk particularly on private land. As a consequence, public land will become increasingly important for large blocks of undeveloped habitat and the area-sensitive forest species they support and the ecosystem services provided.

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THE NORTHERN FOREST FUTURES PROJECT: EXAMINING PAST, PRESENT, AND FUTURE TRENDS AFFECTING FORESTS IN AND AROUND THE CENTRAL HARDWOOD FOREST REGION

Stephen Shifley[1]

The Northern Forest Futures Project is intended to be a window on tomorrow's forests, revealing how today's trends and choices can change the future landscape of the Northeast and Midwest. The research is focused on the 20 states bounded by Maine, Maryland, Missouri and Minnesota—the most heavily forested and most densely populated quadrant of the nation. The three major components of the project are: (a) an assessment of forest resource management issues common to the region, (b) a multidimensional analysis of current conditions and recent trends that characterize the region's forests, and (c) projections of alternative future scenarios to assess the combined impacts of forest succession, land use change, invasive species, biomass utilization for energy, and climate change on the region's forests from 2010 to 2060. There is much to celebrate about Northern forests. In the past century, total forest area increased by 28 percent while total population increased by 138 percent. Volume, biomass, and sequestered carbon have increased steadily over the past 50 years. There are 441,000 jobs in the forestry, logging, forest products, pulp, and paper industries. One out of six forest acres is protected, and populations of 85 percent of forest-associated species appear to be secure. Most states require forest-related planning and provide guidance on best management practices. Nevertheless, there are looming issues that can benefit from a regional perspective on forest resources. Invasive insects and disease, forest fragmentation, loss of forest to development, climate change, and inattention to forest management on private lands are some obvious concerns. Less obvious, but no less important, are the imbalanced forest age-class distribution and associated impacts on biodiversity, matching the capacity of forest industry with compatible resource conservation objectives, and meeting the demands of 124 million predominantly urban residents for wood, water, and recreation.

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BIOFUELS AND BIOENERGY

TECHNICAL CHALLENGES AND OPPORTUNITIES IN COGASIFICATION OF COAL AND BIOMASS

Jagpinder Singh Brar, Kaushlendra Singh, and John Zondlo[1]

INTRODUCTION

Biomass gasification manufacturers are beginning to market 5 to 100 kW capacity gasifiers (e.g., Community Power Corporation (CPC), Littleton, CO and gasifier experimenters kit (GEK), AllPower Labs, Berkeley, CA) for producing electricity and synthetic gas (syngas). These gasifiers operate at 900 to 1000 °C, consuming 1.3 kg of biomass per hour for every kW power output. This corresponds to approximately 3 dry metric tons of biomass per day for a 100 kW gasifier. These types of small gasifiers have shown promise for rural economic development. While these systems run on biomass, inclusion of as much as 30 percent coal will bring down the biomass requirement significantly and increase the total fuel available, allowing for greater application of these systems. However, incorporating coal into these types of small scale biomass gasifiers presents an unknown that will need to be addressed and tested before it can be accepted. This paper presents technical and nontechnical challenges associated with cogasification of coal and biomass mixtures.

GASIFICATION SYSTEM

Gasification is a promising technology for producing syngas from coal and biomass, creating a clean energy fuel and electricity. However, the gasification process is only one of the unit operations in a typical gasification system (Fig. 1). After the feed material (biomass or coal) has been gathered, it goes through preprocessing operations including drying and size reduction. Some other options including torrefying biomass and demineralizing and desulfuring coal may also be considered to reduce downstream cleaning of the product synthesis gas.

In the gasification process, complex hydrocarbons from the feedstock (biomass or coal) decompose in the presence of a gasifying agent (air, steam, or oxygen) to produce smaller molecules like carbon monoxide (CO), hydrogen (H_2), methane (CH_4), and other lower hydrocarbons (Kumar et al. 2009). Different types of gasifiers (fixed bed and moving bed) are used due to variations in feedstock

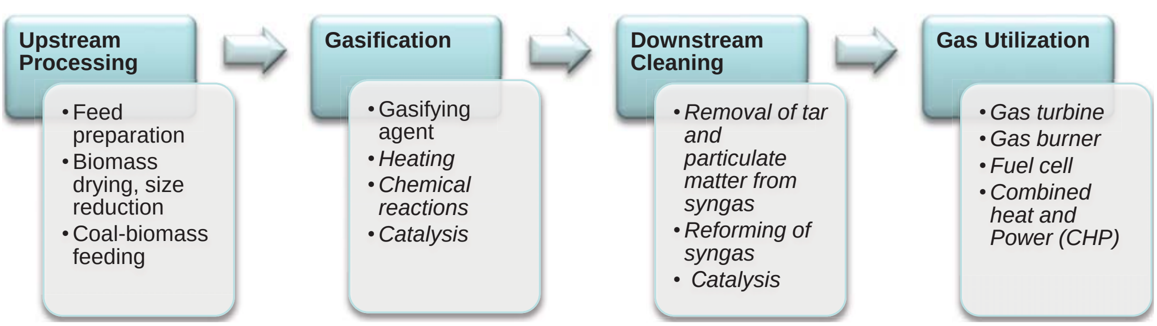

Figure 1.—Process flow diagram showing unit operations involved in a typical gasification system.

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properties and application-specific requirements for the quality of the resulting syngas, such as electricity generation, Fisher-Tropsch liquid (FTL) synthesis, or Dimethyl ether synthesis. Fixed bed gasifiers are divided into three types, (up-draft, down-draft, and cross-draft), depending on the direction of air/gasifying agent flow. In up-draft gasifiers, the gasifying agent is supplied from the bottom to the top of the reactor. In down-draft gasifiers, the gasifying agent is fed from top to bottom. In cross-draft gasifiers, the agent is fed from the left to the right of the reactor. In all three situations, feedstock is fed from the top; however, gas quality and impurities like sulfur, nitrogen, and tar compound vary significantly (McKendry 2002).

In fixed bed gasifiers, four zones (drying, pyrolysis, reduction, and combustion) are formed during the gasification process. In the drying zone, moisture present in the feedstock is removed. After drying, pyrolysis starts at temperatures around 200-400 ºC. In the pyrolysis zone, most of volatile matter is lost, and only fixed carbon is left behind. In the combustion zone, fixed carbon reacts with a sub-stoichiometric supply of oxygen whereupon carbon dioxide is produced. When the oxygen is completely reacted, the reduction of CO_2 takes place, and CO is produced. The water gas shift reaction, which takes place during steam cracking of pyrolysis vapors, is important for increased H_2 content in syngas. In this reaction, CO reacts with steam and produces CO_2 and H_2. This CO and H_2 mainly comprise syngas. Depending upon the supply of gasifying agent, the position of the combustion zone and reduction zone varies. In the down-draft gasifier, gasifying agent is provided from the top of the reactor, and the combustion zone occurs on top. However, in moving bed gasifiers (fluidized, circulating, or bubbling bed), no separate zones are formed. Air is provided above the minimum fluidization velocity of the feedstock, and it behaves like a liquid (McKendry 2002).

After the synthetic gas is produced, downstream cleaning of the gas depends on how the gas will be utilized and includes the following: particulate matter removal, alkali removal, and tar removal. In addition, syngas produced from coal involves sulfur and mercury removal. Syngas produced from coal-biomass mixtures would need downstream cleaning processes applicable to both coal and biomass.

BENEFITS OF COGASFICATION

There has been significant research interest in cogasification due to environmental and technical benefits of various biomass and coal mixtures such as Japanese cedar (*Cryptomeria japonica*) wood and coal (Kumabe et al. 2007), coal and saw dust (Vélez et al. 2009), coal and pine chips (Pan et al. 2000), coal and silver birch (*Betula pendula*) wood (Collot et al. 1999), and coal and birch (*Betula* spp.) wood (Brage et al. 2000). Cogasification of forest residue with coal has rarely been explored (Pan et al. 1999, Ruoppolo et al. 2010).

Environmental Benefits

Coal contains high carbon (60 to 85 percent) depending upon the type of coal (Prins et al. 2006). Gasification of coal produces a gas with a high carbon footprint. Moreover, sulfur present in coal can produce sulfur-oxides (pollutant causing acid rain) during gasification. On the other hand, biomass consists of 15-20 percent fixed carbon, 70-80 percent of volatile matter, moisture, and ash (Kumabe et al. 2007). The greenhouse gas emission index (GHGI) is a unit for measuring and quantifying greenhouse gas emissions. It is defined as the lifecycle greenhouse gas emission associated with the energy products divided by the lifecycle greenhouse gas emissions associated with the fossil-fuel-derived products displaced (Liu et al. 2011). Liu and his colleagues calculated a GHGI of 1.71 for the gasification of coal and 0.96 for the gasification of 60 percent coal and 40 percent biomass. The GHGI decreased in cogasification of coal and biomass as compared to that for coal alone. Also, in gasification of low-grade coal, the addition of biomass is helpful because the low ash content of biomass counterbalances the effect of high ash in coal (Prins et al. 2006). Along with benefits of cogasification of coal and biomass, there are some challenges as well.

Technical Benefits

The use of coal and biomass as a feedstock in gasification provides many technical benefits. Ruoppollo et al. (2010) found an increase from 4.0 MJ/Nm^3 to 4.52 MJ/Nm^3 in heating value of syngas when 30 percent of coal was mixed with biomass for gasification in a fluidized bed gasifier with quartzite bed material as compared to biomass alone. Cogasification of coal and biomass also helped to increase H_2 concentration in syngas. Syngas with a higher H_2 concentration is recommended for conversion into diesel-range hydrocarbons by the Fisher-Tropsch process (Kumar et al. 2009).

Use of biomass with coal in cogasification also helps to reduce smoke caused by sulfur. Blesa et al. (2003) found that saw dust and olive stones (used as biomass) have hydrogen donor capabilities which helped in desulfurization of Maria coal. Moreover, biomass char has high surface area and high reactivity and can be used as a cheap catalyst for the coprocessing of coal and biomass (Zhua et al. 2008).

CHALLENGES

Technical Challenges

Feeding Coal and Biomass to the Gasifier

Feeding coal and biomass to the gasifier is a technical challenge due to the differences in specific gravity of the particles (approximately 1.47 for woody biomass and 1.52 for coal) and the material handling properties of coal and biomass. The differences in density, shape, and size of the coal and biomass particles cause segregation during transport of the mixture and as it is processed inside the gasifier. Cogasification requires preconditioned, uniform mixtures of coal and biomass feedstock (Kumabe et al. 2007, Pan et al. 2000). A durable feedstock material that will not segregate during handling and feeding into a gasification system is essential for producing a homogeneous feedstock. Several options for feeding biomass and coal into the gasification system are shown in Figure 2.

While biomass and coal can be separately fed into a gasifier, doing so complicates plant operation. If coal and biomass are simply blended together and fed into a gasifier, they tend to segregate during

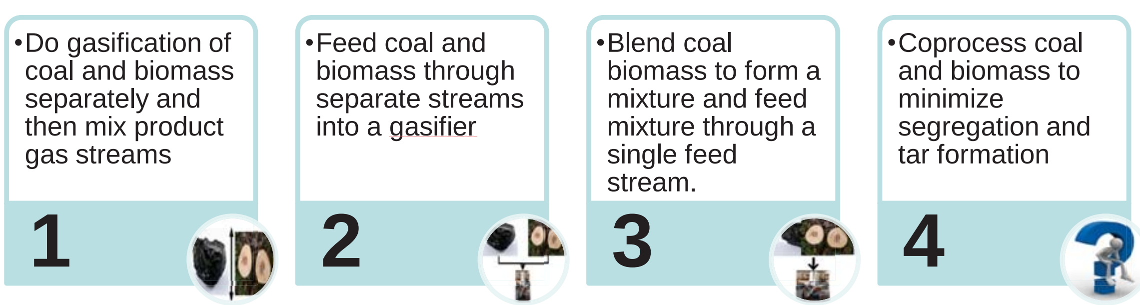

Figure 2.—Options for feeding coal and biomass into the gasification systems.

storage (i.e., piling) and transportation to the gasifier. Inside the gasifier, segregation of coal and biomass particles may also take place due to differences in aerodynamic properties which will limit the benefit of biomass ash catalysis to the gasification of coal. Through pelletizing and briquetting biomass/coal mixtures, the segregation during storage and transportation can be eliminated.

Difference in Gasification Behavior

Gasification is a three-stage process of pyrolysis (devolatilization), gasification (reduction), and combustion. The stages are dependent upon the fixed carbon and volatile matter content of the coal and biomass. Coal mainly consists of 60-70 percent of fixed carbon and 15-20 percent of volatile matter. On the other hand, biomass has 70-80 percent volatile matter and 15-20 percent fixed carbon. Moreover, the devolatilization temperatures of coal and biomass are different. Biomass starts to volatilize at low temperature (200-430 °C) as compared to coal (400-600 °C) (Fig. 3). Different devolatilizing temperatures coupled with segregation of coal and biomass can significantly reduce the volatilization of coal because volatiles formed due to pyrolysis of biomass will not get sufficient time to react with the coal structure.

Additionally, coal and biomass exhibit different combustion characteristics (Fig. 4). While biomass completely burns between 230 to 430 °C, coal combustion begins after 530 °C and is complete at 600 °C. In between the devolatilization and combustion stages, reduction of char formed during pyrolysis takes place.

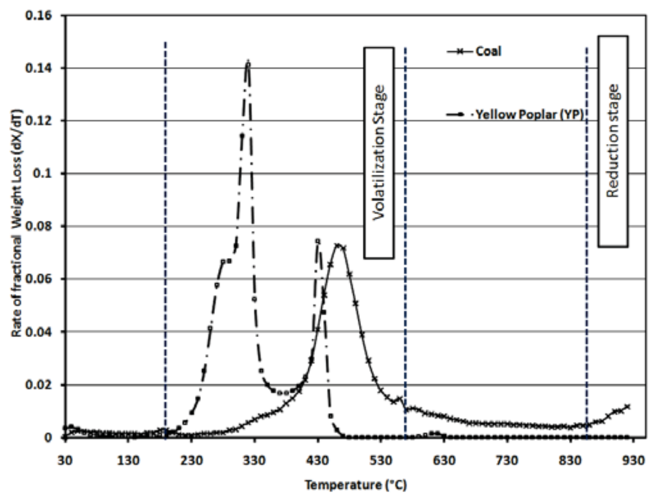

Figure 3.—Rate of fractional weight loss as a function of temperature of West Virginia bituminous coal and yellow-poplar (*Liriodendron tulipifera* L.) obtained from thermo-gravimetric analysis. The samples were heated from 30 to 950 °C under the gasifying agent CO_2 at a flow rate of 50 cm^3/min.

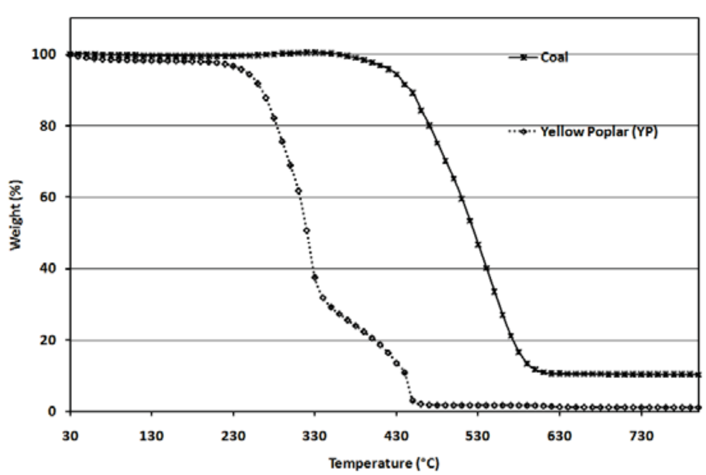

Figure 4.—Weight loss as a function of temperature during combustion of West Virginia bituminous coal and yellow-poplar obtained from thermo-gravimetric analysis. The samples were heated from 30 to 950 °C under air at a flow rate of 50 cm^3/min.

In laboratory experiments, the gasification rates for coal have been shown to be close to 45 times slower than biomass at the same temperature. This can cause buildup of coal in the gasifier and eventual stoppage. Furthermore, biomass has a tendency to form tars during pyrolysis at lower temperatures. One way to address these issues is gasification via a down-draft style gasifier where there is a strong temperature gradient between the oxidative and reducing environments. This kind of design could allow biomass to pyrolyze in the upper, lower temperature section of the gasifier. The syngas/tar mixture is then forced through the hot coal bed where tar cracking can occur. In addition, the coal will likely remain in the ash bed until it enters the high temperature oxidation zone and can supply the fuel for gasifying the biomass. The conditions needed to produce this kind of gasification behavior will have to be identified and may require modification of existing equipment and/or its operation.

OPPORTUINTIES

Technical Opportunities

Coprocessed Coal-Biomass Hybrid Fuel

One option to remove differences in the gasification behavior and decrease the segregation problems is to coprocess coal and biomass to produce a hybrid fuel. Our preliminary lab data showed that a coal and yellow-poplar (*Liriodendron tulipifera* L.) mixture exhibited the individual combustion signatures of coal and yellow-poplar with combustion temperatures from 230 to 630 °C; however, coprocessed samples decomposed in a relatively small temperature range (330 to 600 °C). Similarly, the gasification temperature for the coal and yellow-poplar mixture ranged from 230 to 930 °C with three reaction zones (major reaction zone from 230 to 400 °C and two minor reaction zones from 400 to 530 °C and 830 to 900 °C). Coal gasification had two reaction zones (a major reaction zone at 300 to 530 °C and a minor reaction zone at >830 °C). However, coprocessed samples had just two major reaction zones (330 to 730 °C and >800 °C). Moreover, coprocessed biomass had gasification rates almost four times higher than that of coal alone in the temperature range of 830 to 930 °C.

Preprocessing of Biomass

One feasible option for improving the gasification properties of biomass is through torrefaction. Once torrefied, biomass is more easily reduced in size because it has lost some fibrous nature and tenacity (Bergman et al. 2005). Additionally, the resulting torrefied woody biomass is mainly comprised of cellulose and lignin. By using torrefied biomass with increased lignin content, it should be possible to improve pellet durability when coal is added. Bergman (2005) reported that torrefied pellets possessed an energy density of 14 to 18.5 GJ/m^3, which is comparable to the energy density of bituminous coal (16-17 GJ/m^3).

The fixed carbon content in bituminous coal (50.58 percent) was significantly higher than red maple (*Acer rubrum* L.)(14.71 percent) and yellow-poplar (15.85 percent). Torrefaction increased fixed carbon content of both biomass samples by more than threefold; however, the volatile matter content reduced to half. Similar findings were reported by Phanphanich and Mani (2011) for forest logging residue chips where fixed carbon content increased from 16.07 to 44.76 percent, but hydrogen content decreased. Decreased hydrogen content due to torrefaction reduced the H/C ratio from 0.13 to 0.04 for red maple and from 0.13 to 0.07 for yellow-poplar which was similar to the 0.07 for coal. Using coal alone as a feedstock for gasification produces gas with higher energy content as compared to biomass alone (Liu et al. 2011).

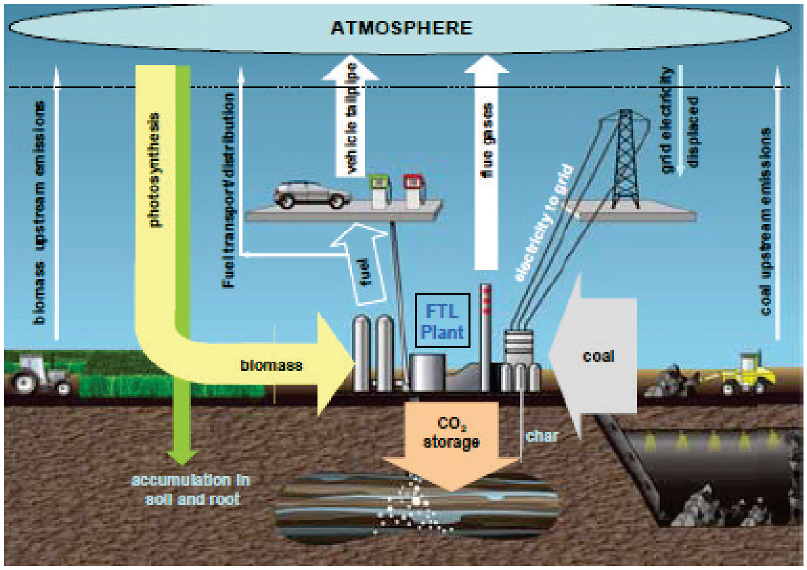

Figure 5.—Schematic of all flows considered in estimating net fuel cycle greenhouse gas emissions. (Source: Larson et al. 2009).

Nontechnical Opportunities

In the Clean Energy and Security Act (July 14, 2009), developing carbon capture and sequestration technologies were emphasized. The Clean Energy Act encouraged production of electricity and transportation fuel with low carbon emissions. According to this act, emission allowance rebates and other incentives would be provided for reducing greenhouse gasses. The concept of selling carbon credits (amount of carbon sequestered) was promoted in this act. Cogasification of coal and biomass produces less greenhouse gas (GHG) emissions than coal gasification alone and helps in reducing carbon footprints. There is an opportunity for seeking carbon credit benefits by producing energy via the cogasification of coal and biomass. Larson et al. (2009) demonstrated reductions in carbon footprint and greenhouse gas emissions from a coal biomass to liquid fuel (CBTL) system utilizing coal and biomass (Fig. 5) for producing Fischer-Tropsch liquids and electricity compared to another coal-based integrated gasification combined cycle (IGCC) with carbon capture and storage (CCS) (90% of CO_2 captured).

In the studied system, the first approach in Figure 2 was adopted to avoid technical complications involved in cogasification. The study considered separate gasification of coal and biomass and then mixed resulting synthetic gases. The mixture of gases was then passed through the Fischer-Tropsch process to convert some gases into liquid fuels. Remaining gases were burnt to produce electricity. During the three processes of gasification, FTL, and electricity generation, the byproducts of carbon emissions were captured and stored using carbon capture and storage technology.

The CBTL system was studied for two types of biomass, namely, corn stover and mixed prairie grasses (MPGs) with flow rates of 3,044 dry tons/day. Coal input rate was set such that FTL liquid could be produced with zero net lifecycle GHG emissions. Some results of the lifecycle analysis are presented in Table 1. In the table, the proportion of biomass in the CBTL system was defined as the percent of the total energy supplied by biomass. The results showed that both coal-based and CBTL systems had 46.7 percent total energy conversion. After performing the carbon balance and converting vented

Table 1.—Electricity conversions and net greenhouse gas (GHG) emissions by coal-based integrated gasification combined cycle (IGCC) system equipped with carbon capture and storage and coal biomass to liquid fuel (CBTL) systems equipped with carbon capture and storage (CCS) and using corn stover and mixed prairie grasses (MPG) (Source: Larson et al. 2009).

	Coal Only	Coal + Stover	Coal + MPG
Percent energy contribution from biomass in the CBTL system (% higher heating value [HHV])	0	37.4%	23.9%
Equivalent energy produced Fisher-Tropsch liquid (FTL) fuel, MW HHV	2,483	521	883
Net electricity to Grid, MW	1,075	246	406
Energy conversion ([energy from FTL+ electricity]/total energy input), %	46.7%	46.7%	46.7%
Carbon (C) input as feedstock, kgC/s	179	39	66
C stored as CO_2	51.1%	51.7%	50.9%
C in char (unburned)	5%	6.9%	6.2%
C vented to atmosphere	18.6%	17.5%	18.4%
C in FTL	24.7%	23.3%	23.9%
C stored, 10^6 tCO_2/yr (90% cap factor)	9.52	2.14	3.49
Net GHG emission ($kgCO_2$/GJFTL HHV)	118	1	-9

carbon into equivalents of GHG emissions, Larson et al. (2009) concluded that the coal-based IGCC systems will have net GHG emissions of 118 $kgCO_2$/GJFTL higher heating value (HHV). In contrast, CBTL plants had either zero or negative GHG emissions.

In the Clean Energy and Security Act 2009, the possibilities of a GHG tax and carbon credit were discussed which may significantly change the economics of the traditional and renewable energy sources. Larson et al. (2009) mentioned that raising GHG emissions price from \$20/tCO_{2equiv} to \$37/tCO_{2equiv} is sufficient to make the CBTL option competitive against coal-based IGCC plant with a corresponding breakeven oil price of about \$56/bbl.

SUMMARY

Cogasification of coal and biomass helps in reducing the carbon footprint and greenhouse gas emissions for energy production from coal. It allows for the opportunity of selling carbon credits. It has other benefits like increased H_2 content in syngas and the reduction of sulfur and mercury pollutants. It also helps in increasing the energy content of syngas. As there are many benefits of cogasification, there are some technical challenges also for using both coal and biomass together in a reactor. Coal and biomass have different density and material handling properties which cause segregation inside the gasifier. Moreover, the different gasification rates of coal and biomass also create problems with unburnt carbons. These challenges can be overcome by coprocessing coal and biomass before feeding them into the gasifier. Coprocessed hybrid fuel showed uniform properties, but reductions in segregation can be expected during gasification. Overall, it can be concluded that cogasification of coal and biomass has advantages and it can create ample opportunities in the energy sector in near future.

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WEST VIRGINIA WOOD WASTE FROM UNCHARTED SOURCES: LOG LANDINGS AND ACTIVE SURFACE MINES

Shawn T. Grushecky and Lawrence E. Osborn[1]

Abstract.—Traditionally, biomass availability estimates from West Virginia have focused on primary and secondary mill byproducts and logging residues. Other sources of woody biomass are available that have not been surveyed. Through a series of field studies during 2010 and 2011, biomass availability estimates were developed for surface mine sites and log landings in West Virginia. Initial estimates indicated approximately 28 green tons of woody biomass were produced for each acre of surface mine cleared. Furthermore, approximately 2.1 tons of woody biomass per acre of forest harvested were found on log landings. Continued research will help to refine our understanding of biomass availability in West Virginia.

INTRODUCTION

Woody biomass availability has gained an increasing amount of attention over the last decade because of an increased desire to replace fossil-based fuels with renewable feedstocks. Most estimates of feedstock availability focus on either primary and secondary processing residues or logging residues. Several states, including Virginia (Parhizkar and Smith 2008), Tennessee (Anonymous 2007), and West Virginia (Spong et al. 2009), have developed reports detailing the availability of primary processing residues in recent years. While primary processing residues represent a significant source of unused material, increased use by wood pellet and engineered product facilities has reduced their availability. Other forms of biomass, such as logging residues, are also actively indexed. Logging residues commonly take the form of tree tops as well as cull and other felled trees remaining after harvest. In West Virginia, substantial amounts of logging residues remain after harvesting (Grushecky et al. 2006), and the relationship between market factors and location have been investigated (Grushecky et al. 2007). Two other potential sources of biomass that have not been quantified in the central Appalachians include biomass on active surface mine sites and residues remaining on log landings after timber harvesting.

West Virginia has an extensive history of coal extraction, especially in the central and southern counties. Many governmental and private groups pursue development opportunities for areas that have been surface mined. One new opportunity for these sites may be projects that produce energy from biomass. This is further warranted because of incentives based on the use of surface mine sites and biomass in the state's renewable energy plan. Because feedstock availability is often a limiting factor for the development of new energy projects, a better understanding of biomass inventories on and adjacent to surface mine sites is needed. Specifically, estimates of recoverable biomass that is produced during mine development are lacking.

During the first phase of mine development, readily marketable roundwood is removed. Following harvesting, contract crews clear the remaining woody vegetation during a second phase often referred

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to as “grubbing.” Fiber cleared during this stage is typically piled and disposed of. The cost for the secondary wood clearing is typically more than $1,000/acre.

Another source of biomass includes material remaining after traditional forest harvesting in West Virginia. Typical timber harvests consist of a centralized log landing that connects a series of skid and haul roads. Logs are often skidded to the log landing where sorting and additional processing takes place. As part of that processing, logs are cut to merchantable lengths, and areas of defect are removed. The result can be a substantial pile of cut-off chunks, unmarketable logs, and unusable branches. This material is often left behind at the end of the logging job and has potential to be utilized as woody biomass fuel, chips, mulch, and other products.

The objectives of this pilot project were to determine the amount of wood fiber that is available on surface mine sites and log landings in West Virginia. This research will help refine biomass availability estimates statewide and serve as an important component of energy-related development in West Virginia.

METHODS AND MATERIALS

Surface Mine Biomass

During 2009 and 2010, approximately 615 acres were harvested for merchantable timber on the research site in central West Virginia. A contiguous 481 acre section within the active mine development area was chosen for this project. Traditional harvesting was complete, and the mining operator was preparing the site for grubbing during the data collection period in the summer of 2010.

The area of the surface mine disturbance was mapped, and a 100 meter grid was established using a geographic information system (GIS). A negative buffer of 50 meters was used to reduce edge effects during sampling. A total of 107 one-fifth acre forest inventory plots were established in each of the grid intersections.

Both standing tree and logging residue information were collected on the site. Species and diameter at breast height (d.b.h.) of standing trees were collected on all plots. Species, d.b.h., and height to a 4-inch merchantable top were recorded on every third plot. Standard diameter tapes were used to measure d.b.h. to the nearest 0.1 inch. Merchantable height was obtained using a survey laser. To determine merchantable heights on those plots where only d.b.h. and species information was collected, a nonlinear model was used to estimate heights based on data from the 33 percent subsample.

Total tree weights were determined using the following nonlinear model that was developed from data collected by Wiant et al. (1977):

$$Green\ Weight = \beta_1 D^{\beta_2},$$

Where β_1 and β_2 are parameter estimates given by Wiant et al. (1977), and D is the diameter at breast height. Logging residue weights were estimated using the equation from Van Wagner (1968):

$$Weight = \frac{11.65\, S \sum D^2}{L},$$

Where weight is reported in tons/acre, *S* is the specific gravity of the logging residue, *D* is the diameter (in inches) of logging residue that intersects with the transect line, and *L* is the length (in feet) of the sampling transect line. A more thorough description of this equation can be found in Van Wagner (1968, 1982).

Log Landing Biomass

A subset of logging jobs within West Virginia were randomly selected from a database provided by the West Virginia Division of Forestry (WVDOF) containing all timber harvests that were completed during the 2010 fiscal year. WVDOF personnel familiar with the selected harvests in each county were asked to provide information that would aid in contacting landowners, avoiding landowner issues, describing relevant conditions, and ultimately finding the landings.

A total of 13 landings, primarily located in northern West Virginia, were visited for this preliminary study. A more intensive ongoing project will investigate biomass loadings at 45 landings throughout the state. Only primary landings, described as the main roadside area where timber was skidded to be merchandised and loaded on trucks to be hauled to primary markets, were included in this study. This study did not include any secondary landings that may have been located within the harvest site used for prebunching or staging activities.

Once a landing was located, each individual pile was numbered. Separate measurements were taken on each pile to characterize its volume. A total of three lengths, widths, and corresponding heights were taken for each pile using a survey laser and/or field tape. Although pile shapes were variable, volume for each pile was computed as a half-ellipsoid using the equation by Hardy (1996, 2011):

$$Volume = \frac{(\pi\, \bar{w}\, \bar{l}\, \bar{h})}{6},$$

Where volume is the pile volume, and *w*, *l*, and *h* are the average width, length, and height measurements recorded for each pile.

Following the collection of pile volume measurements, a transect was established using a surveyors tape along the centerline of the pile corresponding to its longest length. Sampling crews then followed the transect and recorded the starting point and ending point of each void (area where surveyors tape did not contact wood fiber) along the entire length of the pile. Likewise, for each piece that was at least 4 inches in diameter that contacted the transect line, the species, length, and small and large end diameters were recorded. Any defect that reduced the volume of a piece such as dote or hollow area was measured and recorded.

An estimate of actual wood volume as a percentage of the calculated pile volume was computed for each pile using a reduction factor based on the cumulative length of the voids as a percentage of the length of the transect line. The individual piece size data from the transects were used to calculate the total weight for the pile. The weight of each piece was calculated using piece volume (Smalians) and its associated density (species specific) (Panshin and de Zeeuw 1980). The total weight was then divided by the total volume for all pieces intersected by the transect to develop a weighted average density (green) for the landing pile. This density was then multiplied by the pile volume to determine the approximate weight.

RESULTS AND DISCUSSION

Surface Mine Biomass

Data were collected from a total of 84 plots of the 107 established plots. Information from 23 plots was not recorded because the plots were either not directly located in the surface mine permit area or were not in a harvested area.

The most commonly sampled tree was cucumbertree (*Magnolia acuminata*), followed by yellow-poplar (*Liriodendron tulipifera*), sugar maple (*Acer saccharum*), and red maple (*Acer rubrum*). For the purposes of analyses, all species were placed into one of two groups, hard-hardwoods and soft-hardwoods, based on their specific gravity. Hard-hardwoods included red maple, sugar maple, American beech (*Fagus grandifolia*), red oak (*Quercus rubra*), chestnut oak (*Quercus prinus*), white oak (*Quercus alba*), and black birch (*Betula lenta*). All other species were included in the soft-hardwood group. Average specific gravity (green) of 0.49 was used as the cutoff point.

The average diameter of all standing trees was 7.6 inches. Hard-hardwoods averaged 7.8 inches and soft-hardwoods averaged 7.5 inches at breast height. The average diameter at intersection for all species sampled on logging residue transects was 6.1 inches. Hard-hardwoods averaged 6.3 inches and soft-hardwoods averaged 5.8 inches.

Biomass availability per acre before grubbing operations took place was estimated to be 28.3 green tons/acre on this site (Table 1). This included 19.4 green tons/acre of standing trees and 8.9 green tons/acre of logging residues. The majority of this residue was in the soft-hardwood species group. When extrapolated to the entire surface mine permit area, the total amount of biomass resources available would be 17,404 green tons, or approximately 725 truckloads.

This availability reflects the expansion of the sampled surface mine during the 2010-2011 time frame. As the mine continues to operate, additional biomass resources will become available as the mine permit boundary expands. Although caution should be used when expanding this number to all active surface mines in West Virginia, a statewide estimate can be developed. As of September 30, 2010, approximately 11,255 surface mine acres were under “active, moving coal” status by the West Virginia Department of Environmental Protection (WVDEP) (see website at: http://gis.wvdep.org/data/omr.html). Using the estimates developed during this project, approximately 318,516 green tons of biomass would be available in West Virginia.

Table 1.—Total estimated biomass resources available on a surface mining site in central West Virginia

	Biomass resource (tons/acre)		
	Standing trees	Logging residues	Total
Hard-hardwood	6.7	5.1	11.8
Soft-hardwood	12.7	3.8	16.5
Total	19.4	8.9	28.3

Chunk Pile Biomass at Landings

Data collected on the 13 sites included information from both industrial and private landowners. Harvesting information gleaned from WVDOF timbering notifications and observational data on site showed a mixture of harvest types including both even-aged and uneven-aged management strategies. Other activities included a site cleared for a housing development, a site cleared for coal mining activity, one site cleared for a utility right-of-way, and two sites cleared for oil/gas well drilling activity. Reported acreage for the harvest activities ranged from 2 acres up to 180 acres. Average site size was 57 acres.

Obvious signs of firewood "harvesting," either ongoing or in the recent past, were observed on 6 of 13 sites where large chunk piles remained. At some sites this was performed by or for the landowner, but at other sites it could only be attributed to unknown individuals. Discussions with the landowner or neighbors revealed the presence of other inaccessible chunk piles that had been buried, bulldozed over hillsides, or that had been utilized by firewood and mulch harvesters. It was not possible to estimate how much additional biomass material had been present in these chunk piles, but at several larger sites, indications suggested that substantially more biomass remained at the landing than was currently visible to the site crew.

For the 19 chunk piles measured on 13 sites, pile volume ranged from a minimum of 382 ft^3 to a maximum of 23,196 ft^3, with an average size of 3250 ft^3. Computed estimates of the amount of residue in piles ranged from a minimum of 9.5 tons to a maximum of 577 tons, with an average of 72.6 tons of residue.

Total estimated residue on the thirteen sites was 1307.9 tons, from a total of 626 harvested acres combined for all the logging sites. Hard-hardwoods made up 40.5 percent (529.3 tons) of the total weight, and 59.5 percent (777.7 tons) were soft-hardwoods. Computed average residue available at the landing was 2.1 tons/acre of forest harvested. This value will change as more sites are examined.

The average small end diameter of pieces found in the chunk piles ranged from 7.5 inches for chestnut oak to 14.6 inches for red oak (Table 2). The average small end diameter for all species sampled was 10.5 inches. Average piece length ranged from 4.5 feet for blackgum (*Nyssa sylvatica*) to 13.8 feet for black cherry (*Prunus serotina*). The overall average piece length was 10.0 feet (Table 2).

Using these numbers, a statewide total for biomass availability on log landings can be estimated. In 2010, there were approximately 1950 logging sites involving 128,000 acres within West Virginia. Harvested areas ranged from 1 acre to a maximum of 1500 acres. These preliminary results suggest that even after losses due to firewood harvesting, as much as 256,000 tons of woody residue might still be present on the landings from 2010 that might be recovered and utilized. More would be available if it was recovered during logging activities or immediately after the logging job was completed.

Table 2.—Piece size distribution (±standard deviation) for roundwood sampled in landing chunk piles in West Virginia, sorted by descending volume

Species	Small end diameter (inches)	Large end diameter (inches)	Length (ft)	Volume (ft^3)
Sugar maple (*Acer saccharum*)	9.7 (--)[a]	20.6 (--)	13.5 (--)	19.1 (--)
White oak (*Quercus alba*)	11.2 (10.6)	14.6 (10.8)	12.9 (15.0)	10.1 (13.4)
Black cherry (*Prunus serotina*)	8.8 (4.1)	10.0 (4.4)	13.8 (6.4)	8.1 (8.1)
Red oak (*Quercus rubra*)	14.6 (4.8)	16.9 (5.7)	5.0 (3.0)	7.3 (5.8)
Hickory spp. (*Carya spp*.)	8.9 (1.3)	12.6 (0.8)	11.2 (10.1)	7.3 (6.6)
Yellow-poplar (*Liriodendron tulipifera*)	10.9 (3.1)	13.0 (4.0)	9.1 (8.3)	7.2 (8.2)
Red maple (*Acer rubrum*)	8.4 (4.2)	11.1 (5.0)	11.3 (8.5)	5.8 (4.9)
Chestnut oak (*Quercus prinus*)	7.5 (2.1)	9.4 (1.1)	13.5 (5.0)	5.1 (0.1)
Blackgum (*Nyssa sylvatica*)	9.0 (4.2)	11.3 (3.2)	4.5 (0.7)	2.9 (2.2)
Overall Average	10.5 (5.1)	12.9 (5.7)	10.0 (8.5)	7.3 (7.6)

[a]Single measurement

CONCLUSIONS

Significant amounts of woody biomass are generated during surface mining operations in West Virginia. Additional residual woody biomass is left behind at the landings of logging sites related to forest harvesting, property development, and other land clearing activities. Total estimated woody biomass that was potentially available in 2010 from surface mining and log landings combined was 574,000 tons. These new sources of biomass increase earlier estimates of 2.4 million green tons (Wang et al. 2006) by more than 20 percent. Many options are available to capture this waste-stream and use it in value-added opportunities. These estimates can be used to inform both mining operators and surface landowners about the potential biomass resources that become available during these operations.

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FOREST BIOMETRICS

GROWTH AND YIELD FOR A 7-YEAR-OLD YELLOW-POPLAR PLANTATION IN NORTHERN WEST VIRGINIA

John R. Brooks[1]

Abstract.—Results for several major stand level variables from a 7-year-old yellow-poplar (*Liriodendron tulipifera* L.) plantation established in a converted pasture in northern West Virginia were summarized based on initial planting densities of 1,517 trees/ac, 972 trees/ac, 765 trees/ac, and 602 trees/ac. Stand basal area/acre at age 7 was greatest (54.7 ft^2/ac) for the 4 ft spacing and least (22.1 ft^2/ac) for the 10 ft spacing. Average total height for all trees was similar for all spacing treatments except for the 10 ft spacing which was approximately 6 ft shorter at age 7. Based on locally fit logarithmic weight and volume equations, total aboveground green weight and dry weight decreased with an increase in planting density, with the greatest being the 4 ft spacing treatment averaging 26.3 and 10.8 tons/ac, respectively. Outside bark bole volume ranged from 228 to 769 ft^3/ac, while bole green weight ranged from 6.4 to 22.7 tons/acre, depending on planting density.

INTRODUCTION

In the central Appalachian region, few experimental results have been reported for hardwood plantations due to the natural coppice regeneration common to this region. Even less information is available for stand level growth and yield data from successful plantings. Some historical information is available for yellow-poplar (*Liriodendron tulipifera* L.) plantations in Monongalia County, West Virginia (Fithian 1979), Jackson County, West Virginia (Faleru, 1983), Clarion County, Pennsylvania (Grisez 1968), Noble County, Ohio (Funk et al. 1974), and Smith and Trousdale Counties, Tennessee (Clatterbuck 2004). The purpose of this study was to report and develop growth and yield data for planted yellow-poplar in the central Appalachian region based specifically on a planting density study. Stand level growth and yield data are reported for a 7-year-old plantation planted at four different spacings: 4 by 11 ft; 6 by 11 ft; 8 by 11 ft; and 10 by 11 ft.

The study area is located in north central West Virginia near the city of Morgantown. The area is approximately 4 acres in size and was pastured for at least 5 years prior to planting. The site has a northerly aspect and approximately a 30 percent slope. The soils in the study area are classified as Westmoreland silt loams of 25-35 percent slope which are characterized as well drained with a soil depth of 40 inches to bedrock.

METHODS

In late September of 2003, a 4 acre pasture was cut, and 2 weeks later, planting rows were sprayed with a 0.5 percent solution of glyphosate mixed with water. The spray unit utilized was a 50 gallon portable sprayer powered by a 3.5 horsepower motor installed on the back of an all-terrain vehicle (ATV). Planting rows were aligned parallel to the contour and spaced 11 ft between row centers.

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Within each row, planting density treatments (within row densities) were assigned at random at 4, 6, 8, and 10 ft between trees. Planting density treatments were replicated in two blocks, with one planting block located on the lower slope and a second planting block occurring higher on the slope. Seedlings were 1-0 bare root improved yellow-poplar seedlings obtained from the West Virginia Division of Forestry state tree nursery at Clements, WV. Seedlings were hand planted in mid-March 2004 at predetermined planting locations indicated with colored pin flags. During the second and third growing seasons, late spring backpack applications of a 0.5 percent solution of glyphosate mixed with water were applied to provide some herbaceous weed control. During the spring of the fourth growing, an ATV mounted sprayer was used to apply a shielded spray application of a 0.5 percent solution of glyphosate adjacent to each row. No additional herbicide treatments were applied.

Within each density treatment, for both replications, a rectangular fixed area plot was established made up of 5 rows within each treatment area. Average plot size was 0.0733 acre with plot boundaries buffered by at least two additional planting rows. Tree positions were mapped by planting space location, and the first tree in each row was marked with a metal stake to permit individual tree identification through time. At the end of the first, third, and fourth growing seasons, total height to the nearest 0.1 ft using a height pole and diameter at breast height (d.b.h.) to the nearest 0.0001 inch using an electronic caliper were measured for each tree. At the end of the seventh growing season, all trees were remeasured, using an Impulse laser to measure heights. Average number of trees/plot ranged from 115 (4 ft spacing) to 50 trees/plot (10 ft spacing).

To determine accurate estimates of total aboveground green weight, dry weight, green weight of the main bole, and bole ft^3 volume, equations were developed based on the destructive sampling of 57 trees obtained from outside the measurement plots and at nearby even-aged regeneration sites of similar densities on the West Virginia University Research Forest. All live limb segments (excluding leaves) were cut flush with the main stem and weighed as one group. Weights were recorded to the nearest 0.001 g with an electronic scale. The main bole was cut into approximate 1 ft segments with a bow saw and weighed. Tree sections and tops were dried at 70 °C for 1 week and reweighed. Tree ft^3 volume was based on the end diameter measurements of each 1 ft section using Smailian's equation as there was no indication of lower stem butt swell with these small tree sizes. Dry weight was obtained from only 33 of the 57 sample trees. Descriptive statistics for the sample trees are displayed in Table 1. To facilitate stand level estimates of bole green weight (B_GWT), total aboveground green weight of stem and branch wood (TGWT), total aboveground dry weight of stem and branch wood (TDWT), and bole ft^3 volume (B_CUFT), prediction equations were developed using SAS NLIN procedure (SAS Institute Inc., Cary, NC). Prediction equations were of the logarithmic form:

$$Y = \beta_1 D^{\beta_2} H^{\beta_3} \qquad [1]$$

Where Y is the tree level parameter to be estimated, D is d.b.h. in inches, H is total height in ft, and β_i are parameters to be estimated from the data.

Table 1.—Weight and volume sample tree statistics for a yellow-poplar plantation in West Virginia

	n	Mean	Min	Max	SD
D.B.H. (in)	57	0.756	0.210	2.340	0.500
THT[a] (ft)	57	9.1	4.5	23.2	3.9
Bole GWT[b] (tons/ac)	57	2.667	0.158	25.147	4.408
Total GWT (tons/ac)	57	3.525	0.170	30.080	5.579
Total DWT[c] (tons/ac)	33	2.283	0.064	12.924	3.090
Bole (ft^3/ac)	57	0.048	0.003	0.419	0.077

[a] THT is total height
[b] GWT is green weight
[c] DWT is dry weight

Table 2.—Weight and volume equation parameter estimates and model root mean square error (RMSE) for a yellow-poplar plantation in West Virginia

	Beta 1	Beta 2	Beta 3	RMSE
Total DWT	0.2738	1.2914	0.8586	0.473
Total GWT	0.4976	1.4966	0.8795	0.893
Bole GWT	0.0914	1.1864	1.4474	0.644
Bole CUFT	0.0026	1.2595	1.2676	0.006

RESULTS

Nonlinear tree weight and volume equations were fit to the sample data in both weighted (weighted by D^2H) and nonweighted form. The nonweighted parameter estimates were selected since weighted forms showed no improvement in explained error or residual analysis. Parameter estimates and fit statistics are listed in Table 2. All models and model parameters were significant at the p=0.0001 level. Individual tree weights and volumes were estimated for each sample tree and summed by plot for per acre estimates.

Based on the age of these plantations, stand level variables behaved as expected with the greatest density possessing the largest volumes and basal area values. Average (average of the two blocks) planting densities ranged from 1,517 trees/ac with the 4 ft spacing to 602 trees/ac for the 10 ft spacing treatments. Density values are based on actual field counts following planting for each plot. At age 7, percent survival ranged from 86 percent with the 10 ft spacing to 94 percent with the 6 ft spacing. Few survival differences were observed between the 4, 6, and 8 ft spacing treatments. Total basal area/ac ranged from 22 ft^2/ac for the 10 ft spacing to 55 ft^2/ac for the 4 ft spacing treatment. Very little difference was observed in terms of quadratic mean diameter (QMD) between treatments, with the 8 ft and 6 ft treatments showing the largest average diameter at this young age. With respect to total stand height (average height of all trees), little difference was observed between the 4, 6, and 8 ft density treatments, while the 10 ft spacing treatment averaged approximately 6 ft shorter at age 7. Stand development in these variables is shown in Figure 1.

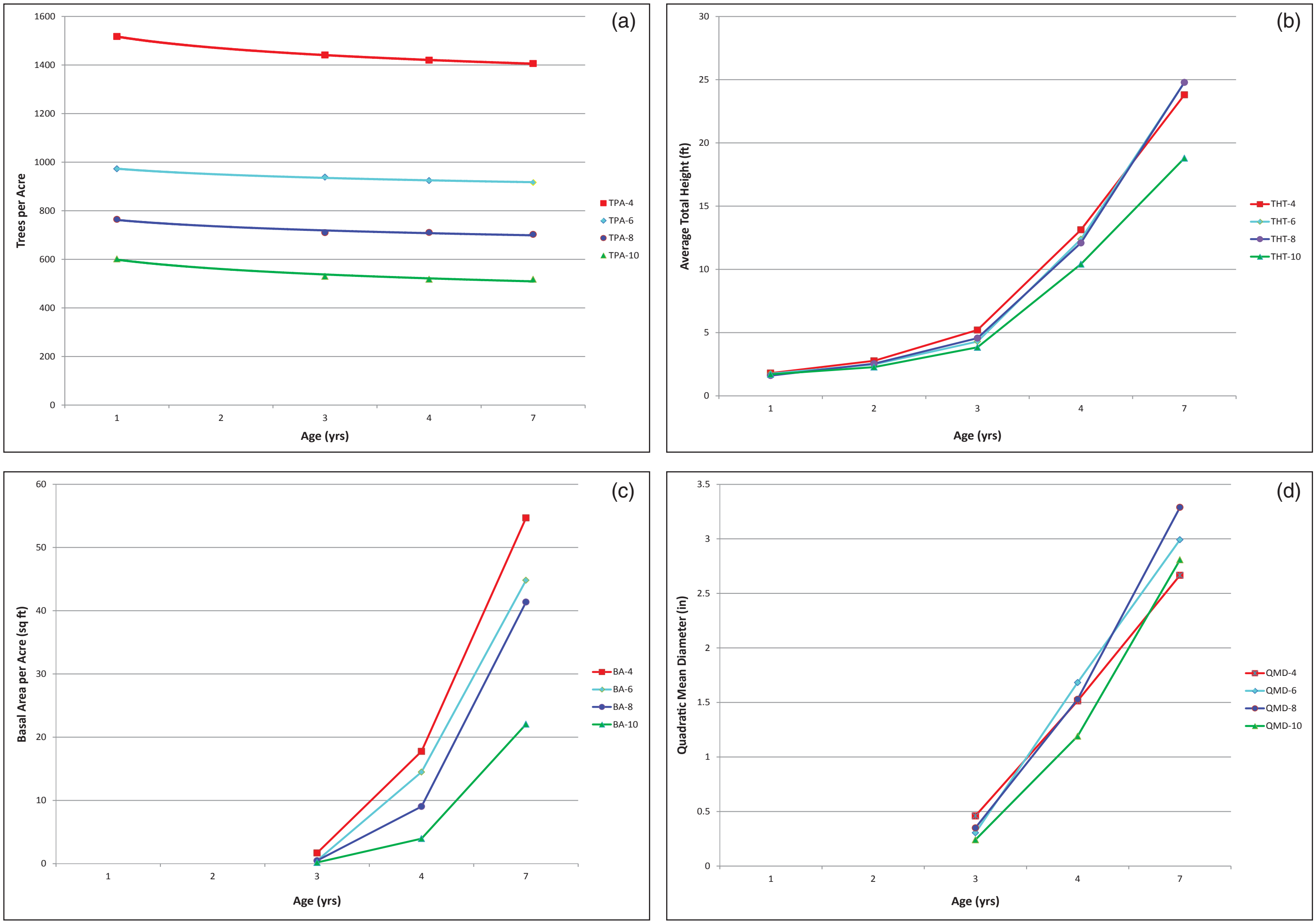

Figure 1.—Average stand trees per acre (a), total height (b), basal area per acre (c), and quadratic mean diameter (d), by age and planting density for planted yellow-poplar in West Virginia.

When considering aboveground weight of stem and branches, both TGWT and TDWT exhibited the same patterns with the 4 ft spacing treatment having the greatest total volume and the 10 ft spacing treatment having the least. Little difference was observed between the 6 ft and 8 ft density treatments. Similar stand development was observed for B_GWT and B_CUFT. At age 7 the greatest volume development was observed with the 4 ft spacing treatment having a TGWT of 26.3 tons/ac, a TDWT of 10.8 tons/ac, a B_GWT of 22.7 tons/ac and a B_CUFT of 769.3 ft^3/ac. Stand development in these parameters are shown in Figure 2.

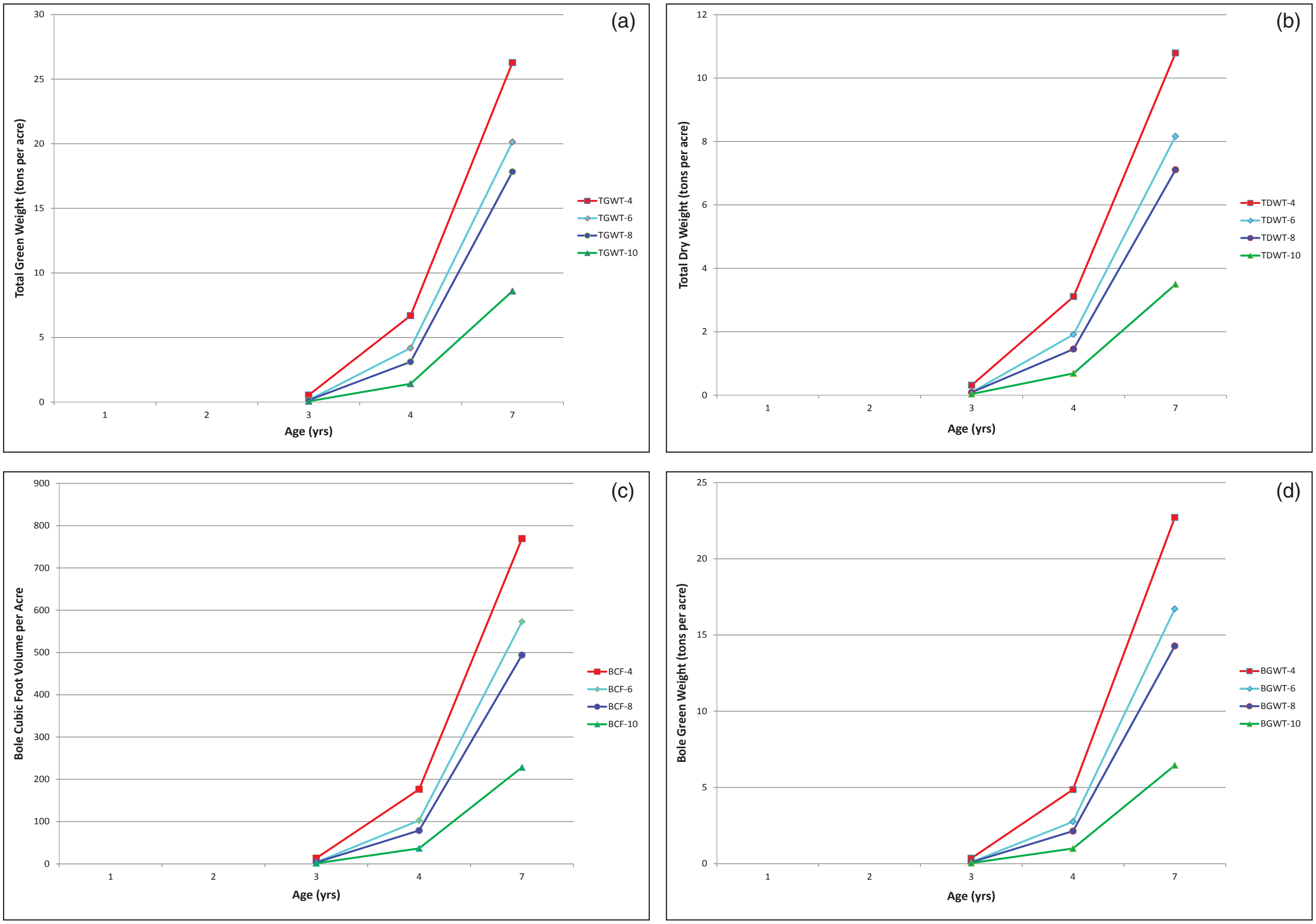

Figure 2.—Average total aboveground green weight per acre (a), total aboveground dry weight per acre (b), bole cubic foot volume per acre (c), and bole green weight per acre (d), by age and planting density for planted yellow-poplar in West Virginia.

DISCUSSION

Although not directly comparable due to different sites, seed sources, ages, and climatic conditions, results from this yellow-poplar density study are similar to those published by Clatterbuck (2004) in Tennessee and Funk et al. (1974) in southeastern Ohio. With proper site selection and herbicide treatments, successful plantations can be established on existing pastures. Although early results can be misleading, the author suggests that planting spacings of 6 ft by 11 ft and 8 ft by 11 ft provide good growth characteristics and good early volume development. Planting at spacing near 10 ft by 11 ft had less volume and average height than other planting densities. The higher density plantings also provide some insurance should planting mortality exceed those achieved in this study.

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INDIVIDUAL TREE, MERCHANTABLE STEM GREEN WEIGHT AND VOLUME EQUATIONS FOR FOUR BOTTOMLAND HARDWOOD OAK SPECIES IN SOUTHEAST ARKANSAS

Paul F. Doruska, David W. Patterson, Matthew B. Hurd, and Jonathan I. Hartley[1]

Abstract.—Equations were developed to estimate outside-bark, merchantable stem green weight (lb) and inside-bark merchantable stem volume (ft^3) for sawtimber-sized Nuttall oak (*Quercus texana* Buckley), overcup oak (*Quercus lyrata* Walt.), water oak (*Quercus nigra* L.), and willow oak (*Quercus phellos* L.) found at two bottomland hardwood sites in southeast Arkansas. Sixty-one trees were used in this study. Trees ranged from 43 to 90 years in age (average of 62 years), 12 to 34 inches in diameter at breast height (d.b.h.) (averaging 19.5 inches), 60 to 120 feet in total height (averaging 94 feet), 27 to 77 feet in merchantable height (averaging 53 feet), and 5.4 to 26.0 inches in merchantable top diameter (averaging 11 inches). Equations were developed by species and employ a combined variable, (d.b.h.^{2} * total height), to facilitate ease of use based on commonly measured inventory attributes. The results of this research should assist those inventorying hardwood sawtimber-sized trees by weight or those working with scaling factors (outside-bark weight divided by inside-bark volume) in southern Arkansas.

INTRODUCTION

Recent buying and selling trends for hardwood sawtimber in southern Arkansas have shifted from a volume basis to a weight basis. Many natural resource professionals use board foot volume equations or tables with conversion factors (Daniels 2001) to convert board foot volume to weight. However, during a forest inventory, regression analysis can be used to develop weight equations, eliminating the need to use conversion factors and the potential errors they introduce.

Equations estimating total tree green weight and green weight to a merchantable top have been developed for several hardwood species in the South (Clark et al. 1986, Schlaegel 1981, Schlaegel 1984, Schlaegel and Willson 1983). However, regression equations are typically applicable only to data similar to that used to develop the equations (Myers 1990), and data from southern Arkansas were not included in these endeavors.

Furthermore, bole weight is influenced by wood properties, which can vary between and within species (Koch 1985, Taylor 1977). Wood properties are also inconsistent between geographic regions, which further illustrates the need for hardwood weight equations that are developed for and applied to trees in southeastern Arkansas.

Arkansas contains approximately 18.75 million acres of timberland (U.S. Forest Service 2011). About 69 percent (12.7 million acres) contain hardwoods, with approximately 16 percent (3 million acres) being bottomland hardwoods (Arkansas Forestry Association 2007) that are common to southeastern

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Arkansas. This large amount of bottomland hardwood acreage, in conjunction with the need to inventory hardwood sawtimber by weight, suggests the need for the development of bottomland hardwood sawtimber weight equations in southeastern Arkansas. The objectives of this research were to develop equations to estimate outside-bark, merchantable stem green weight, and inside-bark, merchantable stem volume for sawtimber-sized Nuttall oak (*Quercus texana* Buckley), overcup oak (*Quercus lyrata* Walt.), water oak (*Quercus nigra* L.), and willow oak (*Quercus phellos* L.) found at two bottomland hardwood sites in southeast Arkansas.

METHODS

Study Sites

Two study sites were selected for this project, one on the Felsenthal National Wildlife Refuge (hereafter referred to as Felsenthal) near Crossett, AR, and the other in Hamburg, AR (hereafter referred to as Hamburg). The two sites were selected and utilized because planned harvesting activities as part of ongoing management at each site allowed for access to felled trees, logging equipment, and equipment operators.

The Felsenthal site has an elevation of 65-75 ft above sea level and consists of a Nuttall oak-overcup oak-willow oak-sweetgum (*Liquidambar styraciflua* L.) cover type. This site was subject to frequent flooding. The Hamburg site has an elevation of 135-145 ft above sea level and consists predominately of a cherrybark oak (*Quercus pagoda* Raf.)-water oak (*Quercus nigra* L.)-white oak (*Quercus alba* L.) cover type, but also includes southern red oak (*Quercus falcata* Michx.), shagbark hickory (*Carya ovata* Mill.), and mockernut hickory (*Carya tomentosa* Poir.). This site was not subject to frequent flooding.

Data Collection

Data was collected at each study site, once before tree harvest (inventory data collection stage) and once after tree harvest (harvest data collection stage). The inventory data collection stage at each stand included randomly selecting and measuring subject trees from the trees marked for harvest. D.b.h. (nearest 0.1 inch), diameter (nearest 0.1 inch) at 1 ft above ground, total height (nearest 1 ft), height (nearest 1 ft) to a called 10-inch top, and bark thickness (nearest 0.1 in.) at 4.5 feet above ground were taken on each subject tree using a diameter tape, a vertex hypsometer, and a bark gauge, respectively. Each subject tree was marked with five bands of paint, with a unique ordering of colors per tree, and a number for identification at the logging deck.

Within 24 hours of the subject trees being felled during the late summer and early fall of 2005, the harvest data collection stages occurred at the study sites. Several measurements and observations were taken on the merchantable boles after they were brought to the logging deck. Total length (nearest 1 ft), inside-bark diameter (nearest 0.1 inch) at the large and small ends of the merchantable bole, age (yr) at the large end of the merchantable bole, outside-bark diameter (nearest 0.1 inch) and bark thickness (nearest 0.1 inch) at 1 foot intervals for the first 8 feet along the merchantable bole and every 3 feet thereafter, were measured for each tree using a logger's tape, calipers, and a bark gauge. Age was determined by counting the growth rings at the large end of the merchandised bole.

Each merchandised bole was then weighed using a digital load cell (Measurement Systems International Challenger 2, Model 3360, 2 lb. increments, Seattle, WA) suspended from a loader and attached to the merchantable bole with chains and tongs. The load cell capacity was 5 tons, so boles expected to weigh over 4 tons were bucked and weighed in pieces. The merchantable boles from Hamburg were bucked into sawlogs of varying lengths. The oaks were cut into 14.5 ft logs, or multiples thereof. The merchantable boles at Felsenthal were used primarily for pulpwood even though they were of sawtimber size, so no set lengths were cut at that site.

Analysis

Smalian's formula (Avery and Burkhart 2002) was used to calculate inside-bark cubic foot volume for each merchantable bole using the diameter and bark thickness measurements taken along each bole. If needed, the weights of the merchandised boles were summed to obtain outside-bark merchantable stem green weights.

Several independent variables were examined for use in ordinary least squares regressions. The combined variable (d.b.h.^{2} x total height) was selected for use in the final models for two reasons: overall model performance as determined by regression diagnostics, and d.b.h. and total height are attributes commonly measured when collecting forest inventory data. Errors from the regression fits were normally distributed (Shapiro-Wilk tests) and residual plots did not suggest the presence of heteroscedasticity.

RESULTS

Table 1 depicts the sample size, mean, standard deviation, and range of age, d.b.h., total height, merchantable stem length, merchantable stem top diameter, and merchantable stem weight by species for the Felsenthal and Hamburg study sites. The average weight/volume ratio did not differ between study sites (two-sample t test; p-value=0.8573) whereas the d.b.h./total height ratio was larger at the Hamburg site (two-sample t test; p-value<0.0001). Subject trees tended to be slightly older at the Hamburg site which may have led to the difference in the latter ratio.

Merchantable Stem Green Weight Equation

The following equation was chosen as the best model form for estimating merchantable stem length outside-bark green weight:

$$\hat{W}_i = b_0 + b_1 D_i^2 H_i \qquad (1)$$

Where: $\hat{W}_i$ = merchantable stem outside-bark green weight (lb) for tree i,
D_i = d.b.h. (in) for tree i,
H_i = total tree height (ft) for tree i, and
b_0, b_1 = parameters to be estimated.

Estimated parameters and fit statistics for equation 1, by species, appear in Table 2. All slopes were significantly different than 0 at α=0.05.

Table 1.—Mean, standard deviation, and range of subject tree age, d.b.h., total height, merchantable stem length, merchantable stem top diameter, and merchantable stem weight by species (sample size) for the Felsenthal and Hamburg study sites

Species	Mean	Standard Deviation	Minimum	Maximum
		Age (yr)		
Nuttall oak (14)	51.1	10.9	45	75
overcup oak (15)	57.0	12.4	43	78
willow oak (14)	57.4	8.2	44	70
water oak (18)	71.1	15.6	55	90
		D.b.h. (in)		
Nuttall oak	17.9	4.1	12.5	24.3
overcup oak	17.5	4.1	11.8	25.5
willow oak	17.7	4.5	11.7	27.7
water oak	23.4	3.9	18.7	34.0
		Total height (ft)		
Nuttall oak	96.2	10.2	83	106
overcup oak	90.2	9.0	73	105
willow oak	91.9	14.9	60	120
water oak	96.3	12.9	69	113
		Merchantable stem length (ft)		
Nuttall oak	54.4	10.5	36.0	65.0
overcup oak	49.1	10.5	27.0	65.0
willow oak	55.3	14.8	31.0	77.0
water oak	53.1	9.8	31.5	66.0
		Merchantable stem top diameter (in)		
Nuttall oak	10.3	3.8	5.7	21.9
overcup oak	9.4	3.9	5.5	16.7
willow oak	10.6	4.5	5.4	26.0
water oak	13.3	4.1	7.7	21.2
		Merchantable stem outside-bark weight (tons)		
Nuttall oak	1.99	0.78	0.93	3.06
overcup oak	1.79	0.78	0.50	3.33
willow oak	2.13	0.93	0.65	3.58
water oak	3.51	1.23	2.23	7.53
		Merchantable stem inside-bark volume (ft^3)		
Nuttall oak	50.9	26.8	23.1	81.8
overcup oak	45.0	23.3	12.7	84.0
willow oak	54.2	16.5	16.5	97.7
water oak	89.0	37.0	52.7	197.2

Table 2.—Parameter estimates and fit statistics for regressions estimating merchantable stem outside-bark green weight (Equation 1, lb) by species and merchantable stem inside-bark ft^3 volume (Equation 2) by species

Equation/species	Parameter	Estimate	Std. Error	P-value
(1)	b_0	976.705	357.067	0.0181
Nuttall oak	b_1	0.091	0.010	<0.0001
	R^2 = 0.8768 Mean Absolute Residual = 0.22 tons; 11.5 percent			
(1)	b_0	590.363	241.911	0.0297
overcup oak	b_1	0.093	0.007	<0.0001
	R^2 = 0.9388 Mean Absolute Residual = 0.16 tons; 12.0 percent			
(1)	b_0	1,856.557	498.173	0.0025
willow oak	b_1	0.074	0.013	<0.0001
	R^2 = 0.7229 Mean Absolute Residual = 0.40 tons; 23.2 percent			
(1)	b_0	932.704	636.795	0.1624
water oak	b_1	0.111	0.011	<0.0001
	R^2 = 0.8687 Mean Absolute Residual = 0.35 tons; 9.7 percent			
(2)	b_0	9.8351	3.9175	0.0274
Nuttall oak	b_1	0.0012	0.0001	<0.0001
	R^2 = 0.9174 Mean Absolute Residual = 4.55 ft^3; 9.6 percent			
(2)	b_0	6.1863	3.3662	0.0890
overcup oak	b_1	0.0012	0.00009	<0.0001
	R^2 = 0.9308 Mean Absolute Residual = 4.47 ft^3; 14.2 percent			
(2)	b_0	20.0948	6.0789	0.0057
willow oak	b_1	0.0011	0.0002	<0.0001
	R^2 = 0.7784 Mean Absolute Residual = 9.65 ft^3; 22.3 percent			
(2)	b_0	3.5669	8.1739	0.6684
water oak	b_1	0.0016	0.0001	<0.0001
	R^2 = 0.8877 Mean Absolute Residual = 9.05 ft^3; 10.8 percent			

Merchantable Stem Volume Equation

The following equation was chosen as the best model form for estimating merchantable stem length inside-bark ft^3 volume:

$$\hat{V}_i = b_0 + b_1 D_i^2 H_i \qquad (2)$$

Where: $\hat{V}_i$ = merchantable stem inside-bark ft^3 volume for tree i, and all other terms as previously described,

Estimated parameters and fit statistics for equation 2, by species, appear in Table 2. All slopes were significantly different than zero at α=0.05.

DISCUSSION

The work herein provides some simple-to-use equations that can assist those estimating either the outside-bark merchantable green weight or the inside-bark merchantable ft^3 volume for four oak species found in bottomland hardwood stands. The larger-sized trees (Table 1) used in this project are indicative of the trees often found in bottomland hardwood stands and represent size classes for which weight equations may not be readily available.

Validation of the equations is suggested before widespread application since trees from only two stands, though representative of bottomland hardwood stands in southeast Arkansas, were used. The range in subject tree size for willow oak was similar to that of both Nuttall oak and overcup oak, yet the willow oak equations possessed the most error, suggesting more work is needed for this species in particular.

When combined with the scaling factor (outside-bark green weight divided by inside-bark volume), results (see Patterson et al. [2011] and Doruska et al. [2006] for scaling factors for these and other hardwood species in Arkansas) one can easily estimate outside-bark merchantable green weight from inside-bark volume estimates or inside-bark volume from outside-bark merchantable green weights.

Whereas this work focused on the entire merchantable portion of the tree stems, Hurd (2006) developed other weight equations involving slightly more complex functional forms for these and other species that allows one to estimate green weight based on d.b.h. and number of logs or merchantable lengths. As a result, one can estimate the green weights for portions of the merchantable stems using the work by Hurd (2006).

ACKNOWLEDGMENTS

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FORESTCROWNS: A SOFTWARE TOOL FOR ANALYZING GROUND-BASED DIGITAL PHOTOGRAPHS OF FOREST CANOPIES

Matthew F. Winn, Sang-Mook Lee, and Philip A. Araman[1]

Abstract.—Canopy coverage is a key variable used to characterize forest structure. In addition, the light transmitted through the canopy is an important ecological indicator of plant and animal habitat and understory climate conditions. A common ground-based method used to document canopy coverage is to take digital photographs from below the canopy. To assist with analyzing below-canopy photographs, the U.S. Forest Service Southern Research Station has developed a computer software tool called ForestCrowns. ForestCrowns calculates canopy transparency (or light transmittance) for digital images taken with standard or fisheye (hemispherical) camera lenses. Specific areas of the photograph can also be targeted to obtain transparency estimates of individual tree crowns. Since images and assessment results can be saved within the program, ForestCrowns can also be used with forest health monitoring programs to detect changes over time in canopy structure due to storm, insect, or disease damage.

INTRODUCTION

There are several ground-based methods currently used for measuring the density of forest canopies. The most basic method involves assessing the canopy visually. Simple visual assessments are quick and require no specialized equipment. A downside of using this method, however, is that the assessments are very subjective and often unreliable (Ghosh et al. 1995, Innes 1988). Some of the factors that can influence visual estimates are: observer experience, observer bias, weather conditions, and lighting conditions.

Another simple, yet more objective, approach for measuring canopy density is to use a spherical densiometer (Lemmon 1956, 1957). A spherical densiometer consists of a concave or convex mirror shaped as a portion of a sphere. The mirror is held horizontally so that it reflects the sky and canopy. A graticule is engraved on the mirror and four equally spaced dots are assumed in each square of the graticule. Readings are taken by counting the number of dots that intersect with the reflection of the canopy. Due to the reflective differences of the canopy from different viewpoints, however, the variation between observer estimates can be significant (Ganey and Block 1994, Vales and Bunnell 1988). Also, the small size and low resolution of the reflected image can result in reduced accuracy of the measurements.

A third widely used ground-based option for measuring canopy density is to photograph the canopy from below and analyze the photographs using computer software. Typically, photographs are taken with a fisheye (hemispherical) camera lens in order to capture the full 180° view of the canopy. A less costly alternative to using hemispherical photography is to take canopy photographs using a standard camera lens (Bunnell and Vales 1990, Macfarlane et al. 2007). Though the use of a standard lens is not suitable for all canopy measurements, it can be used for more localized analyses.

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There are several software programs available for analyzing canopy photographs. Some examples are: Hemiview (Delta-T Device Ltd., Cambridge, UK), Hemiphot (Tropenbos International, the Netherlands), Gap Light Analyzer (Cary Institute of Ecosystems Studies, Millbrook, NY), DHP-TRACWin (Natural Resources Canada, Saint-Hubert, Quebec), CAN-EYE (INRA, Paris, France), and WinSCANOPY (Regent Instruments Inc., Quebec, Canada). The programs vary in price, ease of use, output, and their ability to analyze standard camera images. The purpose of this study was to develop a free, easy to use image analysis software program, capable of measuring canopy transparency from fisheye or standard digital camera imagery.

The ForestCrowns software was designed to be a simple yet effective tool for estimating light transmission through the forest canopy. No specialized photography or computer skills are necessary to collect and analyze a photograph. In addition, the software will be made available to the public at no cost. The basic procedures for obtaining transparency estimates include: photographing the canopy, importing the photo into the ForestCrowns computer program, and delineating the areas of the photograph to be analyzed. Rectangular and elliptical selection tools are available to delineate the analysis region, or the entire image can be selected. Results of the analysis include transparency estimates for each individual selection region as well as the average transparency over all regions. All pictures and analysis results can be stored in a database for comparing seasonal or multiple year evaluations of each site.

PHOTOGRAPHING THE CANOPY

The foundation for the ForestCrowns analysis is the digital image of the canopy. Prior to obtaining the photograph, the best location to position the camera should be determined based on understory vegetation, lighting conditions, and adjacent trees. Photographing below dense understory vegetation should be avoided, as the leaves and branches can block the view of the canopy and produce inaccurate transparency results when the image is processed. Poor lighting conditions and shooting directly at the sun can also adversely affect the ForestCrowns analysis. Sunspots on the image can mask existing canopy structures while overcast skies make it difficult for the software to distinguish between vegetation and sky. Ideally, photographs should be taken when skies are clear and sun is not directly overhead. Finally, the camera placement should not be directly adjacent to tree stems. All images will contain tree stems that partially block the view of the canopy, but the affect is minimized as the distance between the camera and adjacent stems is increased.

Once the photo location has been established, the camera should be mounted on a tripod and leveled so that the camera angle is truly vertical. The use of a tripod minimizes camera movement and prevents blurry images. If periodic photographs will be taken at the same location, the precise location of the camera should be documented using a combination of GPS coordinates and distances to adjacent trees. A metal pin may also be placed in the ground, which can be easily found later using a metal detector if necessary. The radial orientation of the camera should also be documented, as subsequent photos should not only be taken from the same location, but at the same orientation as well. This consistency is necessary in order for ForestCrowns analyses to be comparable. If a hemispherical lens is used, care should be taken to ensure that the photographer is below the camera and not included in the picture. Once the camera has been positioned correctly, the location has been documented, and the lighting conditions are favorable, the photograph can then be taken.

CANOPY ANALYSIS

ForestCrowns can produce transparency estimates for canopy images taken with either standard or fisheye camera lenses. Entire images can be analyzed or portions of the images can be isolated and analyzed separately. In addition, the program can assess multiple photos collectively and provide an average transparency value over all photos. Pictures and analysis results can be stored in a database for comparing seasonal or multiple year evaluations.

Standard Camera Lens

Figure 1 shows an example of a ForestCrowns analysis using a photo taken with a standard camera lens. In this example, the entire image is selected for analysis, but individual regions could also be selected if desired. The transparency value for this example is 21.2 percent, meaning that 21.2 percent of the pixels in the photograph are classified as sky, whereas 78.8 percent of the pixels are classified as leaves, branches, or stems. The program computes transparency by analyzing the relative color of each pixel within the photograph and then classifying each as either sky or biomass. If multiple regions of the image were selected, transparency values for each region would be given as well as an average transparency value over all regions. This type of analysis could be used for plot-level information including: monitoring yearly growth/decline of the forest canopy, leaf area index (LAI) estimation, and estimating light transmission to the forest floor.

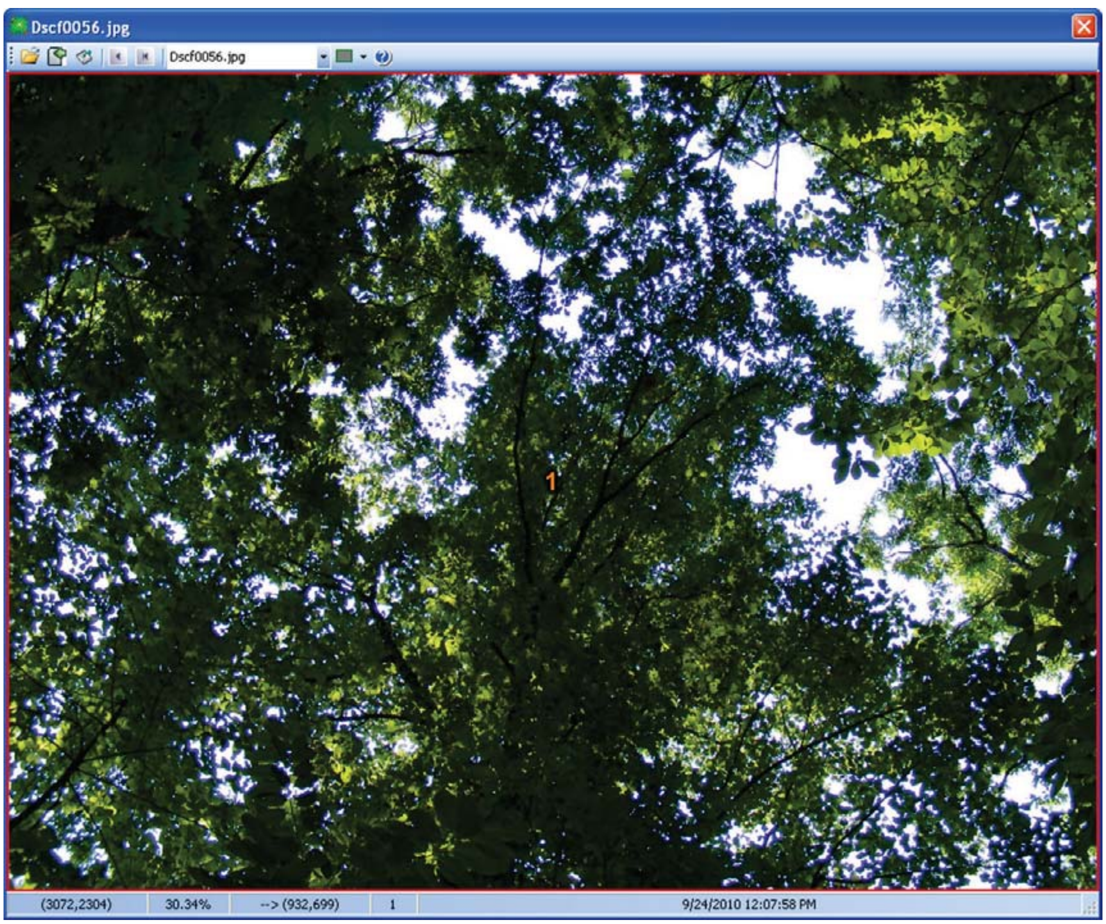

Figure 1.—Example of a ForestCrowns canopy transparency analysis using a photo taken with a standard camera lens. Calculated transparency is 21.2 percent.

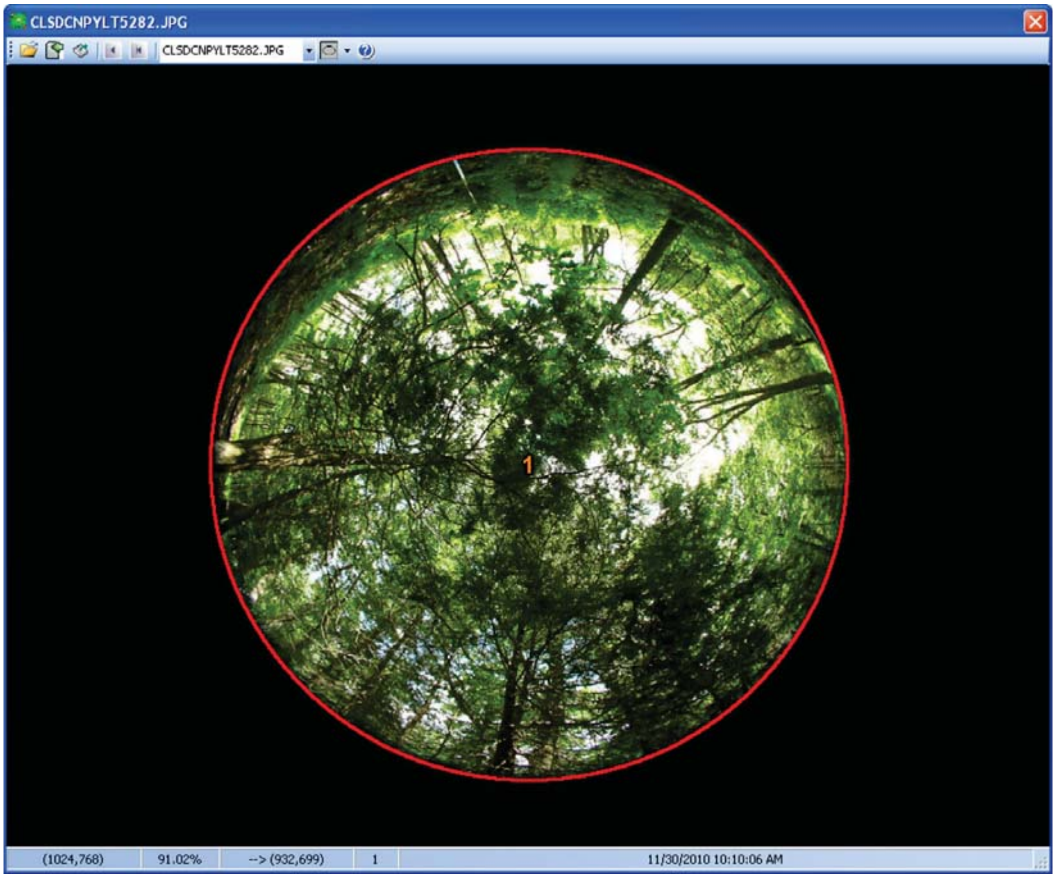

Figure 2.—Example of a ForestCrowns canopy transparency analysis using a photo taken with a fisheye (hemispherical) camera lens. Calculated transparency is 13.8 percent.

For photographs taken with a standard camera lens, ForestCrowns offers a batch processing option for quickly analyzing multiple photos. If this option is used, each individual image will be assessed in its entirety (specific regions within the photo cannot be targeted) and the results will be written to a text file. The batch processing option is not available for fisheye images since the circular image is nested inside a rectangular frame and cannot be analyzed without first selecting the circular region.

Fisheye Camera Lens

Photographs taken with a fisheye (hemispherical) camera lens are commonly used for ground based canopy analysis because they allow for a larger coverage area than photographs taken with a standard lens. A fisheye lens captures everything above the horizontal plane of the camera. One difference between a photograph taken with a fisheye lens and a photograph taken with a standard lens is that the resulting image is circular. Therefore, before a fisheye image can be analyzed in ForestCrowns, the circular area must be delineated using the elliptical selection tool. Figure 2 shows an example of a ForestCrowns analysis of a fisheye image. The red outline in the image represents the outer edge of the analysis region. For this example, the transparency value is 13.8 percent.

Fisheye image analyses in ForestCrowns can be used for monitoring gaps in the canopy and for estimating light transmission to the forest floor. Gap analysis can show evidence of forest disturbances (blow-downs, insect infestations, disease) while light transmission estimates are important for predicting such things as plant regeneration potential, soil moisture retention, and subcanopy climatic conditions.

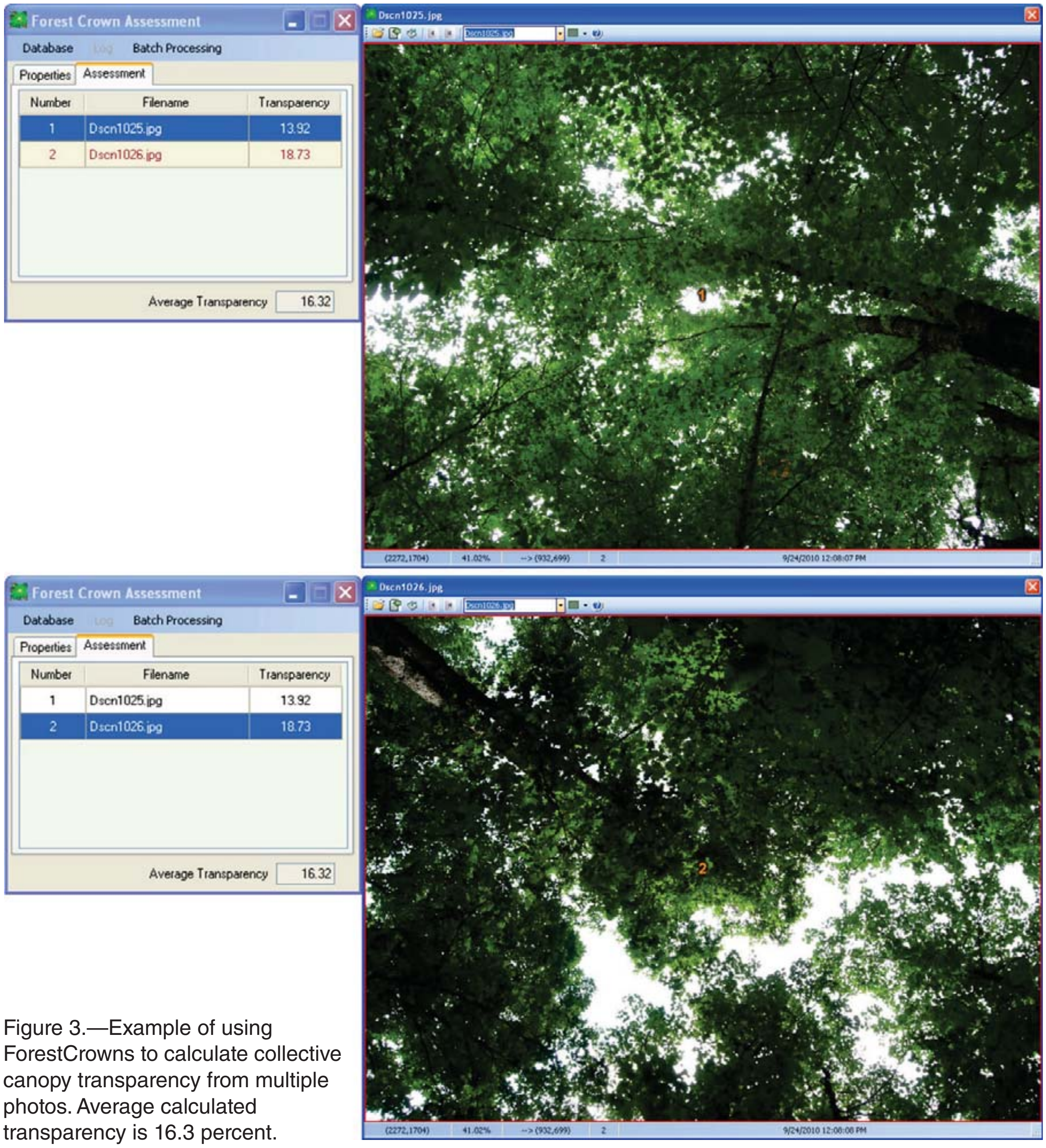

Figure 3.—Example of using ForestCrowns to calculate collective canopy transparency from multiple photos. Average calculated transparency is 16.3 percent.

Multiple Photos

In addition to being able to analyze individual photos, ForestCrowns can also analyze multiple photos collectively. The images are assessed as a group, which differs from the batch processing option where each photo is assessed individually. When multiple photos are imported into the program and the analysis regions are selected, ForestCrowns generates transparency values for each photo as well as the average transparency for all photos. This feature works with both standard and fisheye imagery. Figure 3 shows an example of analyzing two photos collectively. The first photo has a transparency value of 13.9 percent while the second has a transparency value of 18.7 percent. In the lower right corner of the results window, the average transparency value for the two photos is shown as 16.3 percent. Multi-photo assessments can be used for forest-level canopy analyses such as monitoring yearly canopy growth/decline, LAI estimates, and estimates of light transmission to the forest floor.

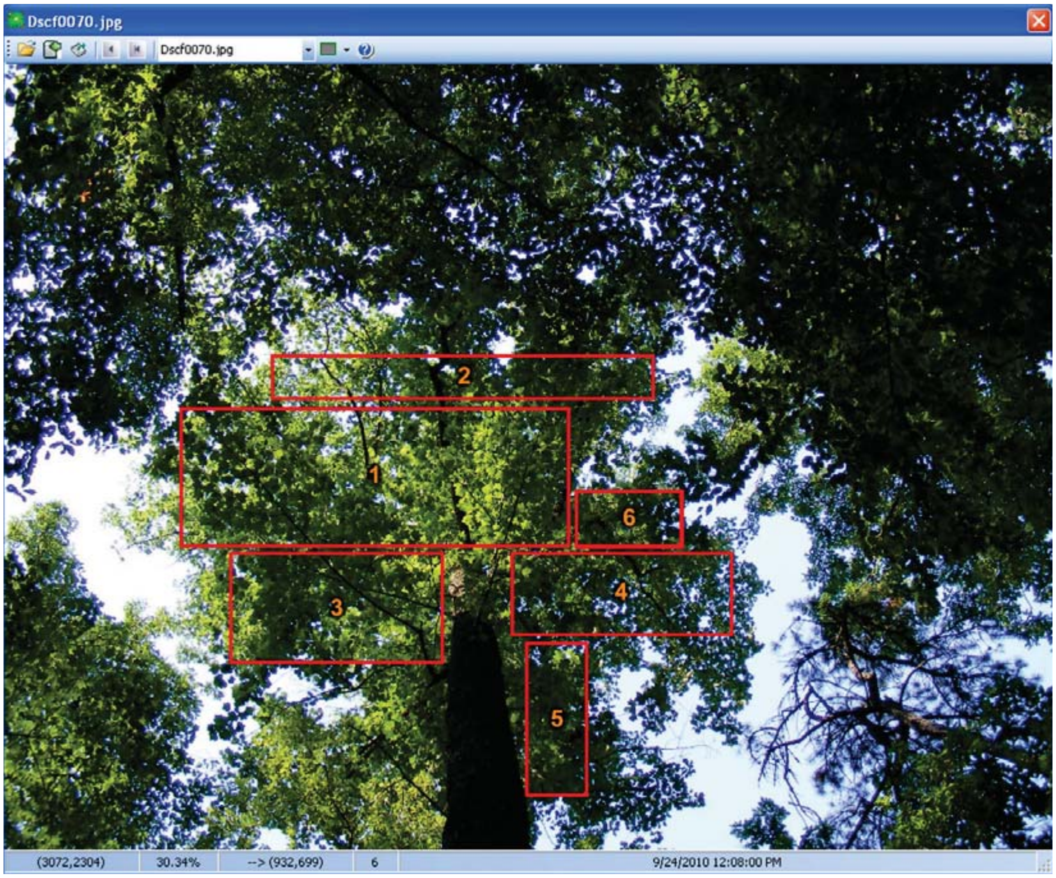

Figure 4.—Example of using ForestCrowns to calculate transparency of an isolated tree crown using multiple selection regions.

INDIVIDUAL CROWN ANALYSIS

For instances where an individual tree crown can be isolated from the rest of the canopy, ForestCrowns can be used to assess the transparency of the crown. Figure 4 shows an example of an isolated tree crown. Multiple selection regions are drawn to cover as much of the crown as possible. Transparency is calculated for each individual region and the weighted average crown transparency is determined (Fig. 5). The individual transparency values range from 5.8 percent to 21.3 percent. The average transparency value for the crown is 13.7 percent. Some of the potential uses for individual crown analysis include: monitoring yearly growth/decline of individual tree crowns; early detection of disease, insect or storm damage; and monitoring health treatments.

SUMMARY

One alternative to using aerial photography or satellite imagery to analyze forest canopies is to assess the canopies from below using digital photographs. ForestCrowns is a simple and cost-effective software tool developed by the Forest Service Southern Research Station that can be used to determine canopy transparency values from ground-based digital photographs. The program can be used to assess photos taken with a standard or fisheye camera lens and is also capable of processing multiple images collectively. If an individual tree crown can be isolated from the rest of the canopy, crown transparency can be determined as well. ForestCrowns can be used to: monitor growth/decline of forest canopy; estimate LAI; measure light transmission to the forest floor; analyze canopy gaps; detect disease, insect, or storm damage; and monitor health treatments. The expected release date for the software and user's guide is 2012.

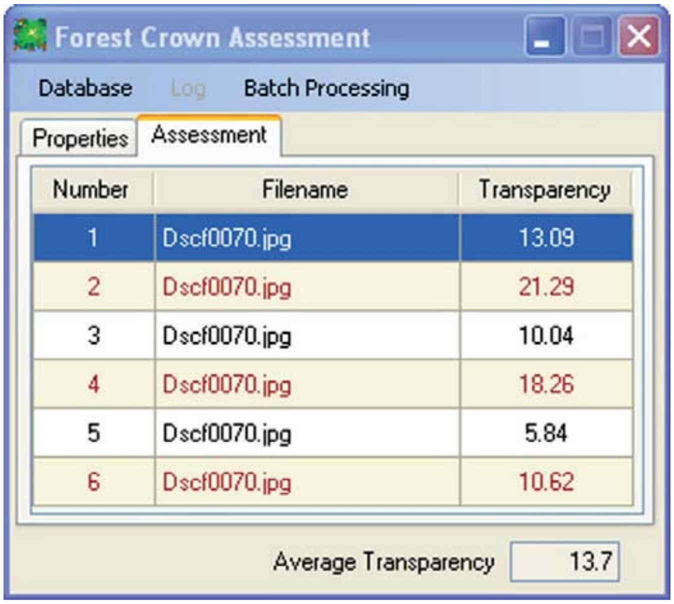

Figure 5.—Results of the ForestCrowns analysis shown in Figure 4. Average calculated crown transparency is 13.7 percent.

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FOREST ECOLOGY AND PHYSIOLOGY

EFFECT OF WEED CONTROL TREATMENTS ON TOTAL LEAF AREA OF PLANTATION BLACK WALNUT *(JUGLANS NIGRA)*

Jason Cook and Michael R. Saunders[1]

Abstract.—Determining total tree leaf area is necessary for describing tree carbon balance, growth efficiency, and other measures used in tree-level and stand-level physiological growth models. We examined the effects of vegetation control methods on the total leaf area of sapling-size plantation black walnut trees using allometric approaches. We found significant differences in total tree leaf area and cross-sectional stem area at breast height between trees receiving 100 percent (pre-emergent and post-emergent) weed control treatment and those receiving pre-emergent control or no control. Additionally, neither branch height nor weed control treatment factored significantly in determining branch leaf area (BLA), allowing for the use of a universal equation for calculating BLA in young black walnut plantations.

INTRODUCTION

One of the key objectives for tree plantations is the rapid growth of timber volume over short periods of time. Meeting this goal is dependent upon a number of cultural factors; one of the most important of these factors is controlling the impact of competing herbaceous vegetation during early plantation development. Studies have shown that newly established afforested plantations benefit strongly from control of competing vegetation (Cogliastro et al. 1990, Fournier et al. 2007). For example, Willoughby (1999) examined the impact of five levels of herbaceous control, ranging from none to complete control (i.e., bare earth), on Corsican pine (*Pinus nigra* Arnold ssp. *laricio* Maire) and Norway maple (*Acer platanoides* L.). The bare earth treatment in Norway maple resulted in 19.9 percent higher average growth in stem diameter over the next closest treatment. Meanwhile, a 57.4 percent growth disparity occurred between the bare earth treatment and the untreated management.

Competition can affect trees in a number of ways. Although competition for belowground resources is important during plantation establishment (Ares and Brauer 2005, Burgess et al. 2010, Wagner et al. 2006), aboveground competition influences crown development, perhaps by changing the amount of leaf area displayed on branches or the number of branches a tree maintains (i.e., change in crown architecture). Development of total leaf area (TLA) allometric relationships can help to allude to this difference. This type of leaf area analysis has been used in many species of conifers, such as eastern hemlock (*Tsuga canadensis* (L.) Carriére) (Kenefic and Seymour 1999), balsam fir (*Abies balsamea* (L.) Mill.) (Coyea and Margolis 1992), and ponderosa pine (*Pinus ponderosa* C. Lawson) (O'Hara and Vallappil 1995), but has yet to be examined extensively in hardwood species.

In conifers, most leaf area models are based on either sapwood area or diameter (Kenefic and Seymour 1999). Sapwood area-based models, either for sapwood measurements taken at the base of the live crown or at breast height, have broad empirical support (Coyea and Margolis 1992, Long and Smith 1989) and are supported by the pipe model theory (Shinozaki et al. 1964). However, these sapwood-based models require destructive sampling to develop and are likely not significantly

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different from diameter-based models in young hardwood plantations, because a high proportion of cross-sectional area at breast height (CSA) is sapwood anyway.

We hypothesized that the relationship between TLA and CSA will vary by weed control treatment in black walnut (*Juglans nigra* L.). Additionally, we believe a relationship will exist between TLA and individual weed control treatments, with the highest TLA demonstrated in trees receiving "Full" treatment and the smallest TLA demonstrated in trees receiving no weed control.

STUDY AREA

The sample trees used for this study consisted of young, small-diameter (11.7 mm to 31.8 mm diameter at breast height[d.b.h.]) black walnut trees selected from plots demonstrating three different levels of herbaceous vegetation control on afforested farmlands. Trees ranged in age from 2 to 4 years old, had never been pruned, and all were first generation crosses from the Purdue #1 genotype (Beineke 1990). The first treatment, hereafter referred as "Full," consisted of 100 percent control of competing vegetation. This method involved the use of an initial pre-emergent inhibitor with subsequent use of glyphosate applications for control of emerging vegetation. Sample trees of this treatment were located at approximately 40˚22'51" N and 86˚59'22" W in the New 76 Plantation owned by ArborAmerica, Inc. (Westpoint, IN). The "Full" treatment trees from this plantation were used because the cross-sectional areas at breast height more closely resembled trees of the other two treatments; this would better isolate competition effects from tree size effects on leaf area display. The next treatment, "Pre," was application of the pre-emergent herbicide only. Any vegetation that emerged following this treatment was left to grow and compete. The final treatment, "No," involved no input for controlling competing vegetation. Sample trees of the "Pre" and "No" treatments were located on three different test plots within the Highlands plantation, 40˚23'23" N and 87˚02'53" W, also owned by ArborAmerica, Inc. Both the New 76 and Highlands plantations lie on the same large complex of Elston sandy loams and loams, although the Highland plantation does have some Coloma sands (NRCS 2011). Both plantations are sprayed annually in late May with azoxystrobin for walnut anthracnose that, if left untreated, would lead to early leaf abscission (i.e., in mid-August) within these plantations.

METHODS

We used stratified random sampling to collect all leaves from 38 branches across 32 sample trees from August 25 through September 5, 2010. Specifically, trees were randomly assigned to have branches sampled from the upper, middle, or lower third of the live crown. If branches were inadequate (i.e., damaged or missing leaves that had already senesced) or not available in the assigned third for a given tree, the tree was randomly reassigned to another strata. All trees had at least one branch sampled and a few had two branches sampled. In total, we sampled 15 branches from 13 trees in the "Full" treatment, 16 branches from 14 trees in the "Pre" treatment, and 7 branches from 5 trees in the "No" treatment. Collected leaves were kept refrigerated at 2˚C after collection. We then recorded two diameters at breast height perpendicular to one another with digital calipers and recorded tree height with a telescoping height pole. Attachment heights and basal diameters were recorded for every branch.

Leaf samples for each branch were scanned with an Epson 10000XL scanner. WinFolia 2009a (Regents 2009) was used to determine the leaf area to the nearest 0.01 cm^2 for each scanned image. To save time, subsamples of 20 leaves were collected from larger branches that held more than 30 leaves. Once scanned, leaves from each branch were oven-dried at 70 ˚C for 72 hours. Weights of the samples and subsamples were recorded to the nearest 0.01 g. Specific leaf area (SLA) was calculated for all samples or subsamples by dividing the total leaf area of each branch by the oven-dry leaf weight of the same branch. SLA from subsamples was used to estimate total branch leaf area by multiplication with total oven-dry weight of all leaves on those branches.

Analysis

Following the procedures of Kenefic and Seymour (1999), models were developed to estimate branch-level leaf area from branch cross-sectional area, branch height, and vegetation control treatment. The full model included all of these variables and their interactions to estimate the branch leaf area. Additional models were run that estimated branch leaf area with each of the variables separately.

The most parsimonious branch-level model was used to develop treatment-specific tree-level models by summing branch-level estimates across all branches on a given sample tree. Tree-level models included the response variables CSA, d.b.h., tree height, and weeding treatment. Models were simplified wherever possible by testing for common intercepts and slopes among weeding treatments.

The final branch-level and tree-level models were tested using standard procedures for normality, homoscedasticity, and independence (Zar 2010). All analysis was conducted using R 2.12.1 (R Development Core Team 2010). Significance was tested at $\alpha = 0.05$.

RESULTS

Branch Level

We found a mean of 15.7 branches per tree in the "Full" weed control treatment and means of 13.7 and 10.8 in the "Pre" and "No" treatments, respectively (Table 1). Overall, the average SLA across all three treatments was 105.2 $cm^2 g^{-1}$. Individually, the "No" treatment displayed the highest average SLA value of 109.5 $cm^2 g^{-1}$ the "Pre" and "Full" treatments had an SLA of 107.2 and 101.5 $cm^2 g^{-1}$, respectively (Fig. 1). These differences were not significant, however ($F = 2.577$, $p = 0.091$).

Examination of branch-level models suggested that only branch cross-sectional area was needed to adequately predict leaf area. This finding was somewhat surprising as branch height, or one of its derivatives, has generally been found to be important in predicting branch-level leaf area (e.g., Kenefic and Seymour 1999). However, we found no evidence of its effect on the branch leaf area and branch cross-sectional area relationship ($F = 0.439$, $p = 0.512$).

Table 1.—Treatment-specific mean specific leaf area (SLA; ± 1 standard error), average height of first branch (AHT), average number of branches per tree (Nbr), and average number of branches found below breast height (NbrBH)

Treatment	SLA ($cm^2 g^{-1}$)	AHT (cm)	Nbr (no.)	NbrBH (no.)
Full	101.5 ± 1.8	53.4	15.7	9.7
Pre	107.2 ± 2.8	59.5	13.7	6.6
No	109.5 ± 2.7	53.9	10.8	6.1

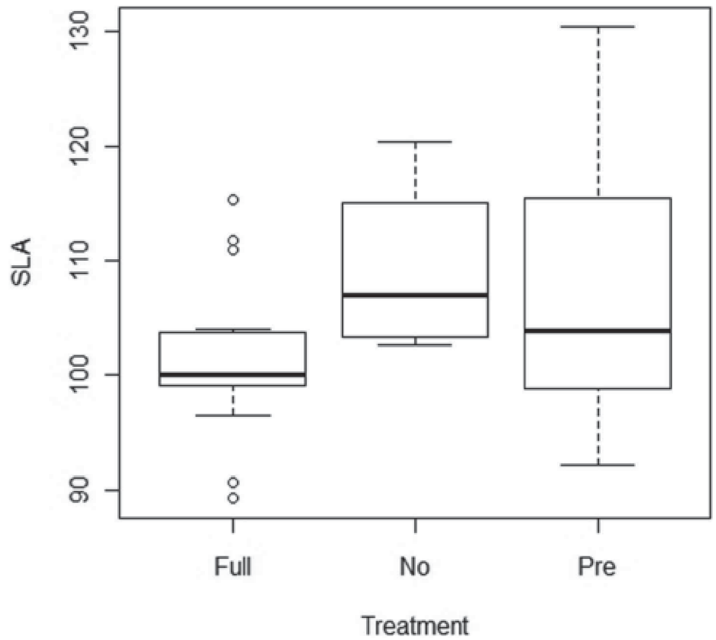

Figure 1.—Boxplot of specific leaf area (SLA) in cm^2 per oven-dry g for the three weed control treatments.

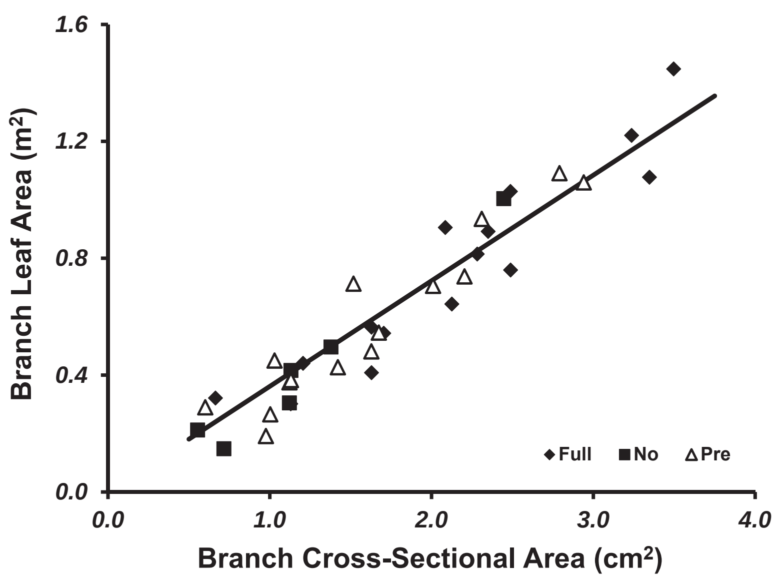

Figure 2.—Relationship between the branch leaf area and the branch cross-sectional area for all trees across all weeding treatments. Treatment-specific models were not significantly different at $\alpha = 0.05$.

We also did not observe a difference among the three vegetation control treatments on the branch-level leaf area relationship through an effect on either the slope or intercept of the model (all models p > 0.678). Therefore, the most parsimonious branch-level model was:

$$BLA = 3614.5 \times BSA \qquad (1)$$

where BLA is the branch-level leaf area in cm^2 and BSA is the cross-sectional area of the base of the branch in cm^2. This relationship was quite significant ($F = 42.4$, $p < 0.001$) and had an adjusted R^2 of 0.91 (Fig. 2).

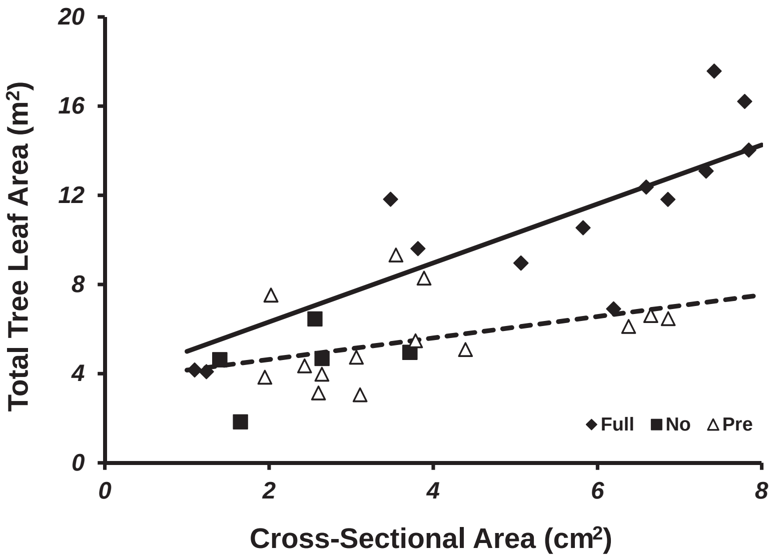

Figure 3.—Treatment-specific relationships between cross-sectional area at breast height and total tree leaf area. The "Full" treatment model (equation 2) is shown as the solid line. The "No" and "Pre" treatments were not significantly different from one another at $\alpha = 0.05$ (equation 3) and are shown as the dotted line.

Tree Level

Total tree leaf area was strongly related to CSA ($F = 44.11$; $p < 0.001$) with an adjusted R^2 of 0.538. Adding vegetation control treatments improved fits considerably ($F = 8.10$; $p < 0.001$). After testing linear models for common intercepts and common treatments among the treatments, we found that the most parsimonious model included a shared intercept among all treatments and a different slope for only the "Full" treatment (Fig. 3). This model was ($F = 58.29$; $p <0.001$):

$$TLA = 3.675 + 1.323 \times CSA \quad (2)$$

for the "Full" treatment, and:

$$TLA = 3.675 + 0.481 \times CSA \quad (3)$$

for the other two treatments, where TLA is in m^2 and CSA is in cm^2. The model had an adjusted R^2 of 0.756.

DISCUSSION

In young black walnut plantations that have not reached crown closure, cross-sectional area appears adequate to predict TLA if plantations are under the same cultural regime. If plantations differ in the level of herbaceous control, plantation-specific relationships may need to be developed. Our results suggested that only the "Full" vegetation control required a separate model; however, we recognize that the small sample size of the "No" vegetation control treatment (n = 5) likely limited the statistical power to separate from the "Pre" treatment. This was unavoidable in our sample because most walnuts under this cultural regime had died or shed leaves much earlier in the growing season due to the intense competition for light from surrounding taller weeds. Walnut has been shown to be extremely sensitive to competition (Ares and Brauer 2005); for example, after five growing seasons, Fournier et al. (2007) observed significant improvement in height and diameter growth for trees in young plantations with chemical release treatments over mechanical release treatments, largely because the mechanical treatments resprouted and acted as strong competitors with the walnut for both light and belowground resources.

Branch-level leaf estimates did not differ by cultural treatment or by height of the branch, allowing for use of a universal branch level equation. Likely, branch height was not as important as we initially thought because the trees were not large or old enough for that factor to become significant. However, Gilmore and Seymour (1997) observed even in mature trees that branch height may not be important to modeling BLA; their study of crown architecture of balsam fir used a generic branch level formula within four crown positions (open-grown, codominant, intermediate, and suppressed) with only minimal sacrifice to the overall accuracy of the model.

This disparity in effects of weed control on the tree-level and branch-level leaf area equations demonstrate that treatment-level differences are not a function of differing leaf area display on the same size branches across treatments, but instead a change in the crown architecture in response to vegetation control. In this study, the presence of herbaceous vegetation likely influenced the number of branches that develop per tree, which in turn influenced the depth of the live crown. This conclusion is consistent with Marino and Gross (1998) on willow species planted in southwest Michigan. They observed that trees grown in the presence of weeds initiated fewer branches and had fewer living branches than those grown in weed-free conditions.

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A MULTI-CENTURY ANALYSIS OF DISTURBANCE DYNAMICS IN PINE-OAK FORESTS OF THE MISSOURI OZARK HIGHLANDS

Chad King and Rose-Marie Muzika[1]

Abstract.—Using dendrochronology and growth release approaches, we analyzed the disturbance history of shortleaf pine (*Pinus echinata* Mich.) white oak (*Quercus alba* L.) forests in the Missouri Ozark Highlands. The objectives of this study were to (1) identify growth release events using living and remnant shortleaf pine and white oak, (2) analyze the temporal variation of canopy disturbances, (3) examine how topographic variation affects disturbance, and (4) note growth releases that occur during and subsequent to selected drought events. These data were used to more fully understand the contribution of disturbance types and the effects of changing disturbance regimes on the structure of the Ozark pine-oak forests. Comparisons were made among trees within a stand and between stands at two study sites to contrast the frequency and magnitude of canopy disturbance. Differences in the dynamics of historic disturbance events between stands were reflected in temporal variation of establishment for both shortleaf pine and white oak. Topography affected both the frequency and synchronicity of disturbance events and therefore contributed to heterogeneous forest structure within a limited spatial extent. Releases of varying magnitude appear to occur during and subsequent to prolonged drought events that likely reflect partial canopy dieback or tree mortality that is either directly or indirectly caused by drought conditions. These data suggest wide ranging temporal and spatial variation in canopy disturbance events over the 400 years of analysis.

INTRODUCTION

The presettlement forest communities of the Missouri Ozarks ranged from closed canopy forests of hardwoods, namely oaks (*Quercus*), to open oak woodlands and pine (*Pinus echinata* Mill.) savannas with a continuum of forest community types. Although many of the controlling factors for vegetation included physical site attributes such as soil, parent material, and topography, the type and frequency of disturbance also influenced vegetation composition and structure, particularly in the wide ranging intermediate types, generally referred to as pine-oak forests.

The general objective of this research was to address the historical disturbance dynamics of shortleaf pine-oak communities in the Ozark Highlands of Missouri and to contrast the historical structure of pine-hardwood forests with current forest composition and dynamics to understand long-term changes in forest ecosystems of the lower Midwest. Little is known about the variation in disturbance type in the Ozark Highlands. Previous disturbance research in the Missouri Ozarks clearly identified the importance of fire in determining forest structure and composition.

Fire regime, however, is strongly influenced by topography and human activity (Guyette et al. 2002, 2003). Although fire may have been the dominant form of disturbance in homogeneous landscapes, e.g., plains and plateaus, many topographically complex areas experienced very little fire over many centuries (Guyette et al. 2007).

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Little is known about the frequency and magnitude of other disturbance events such as wind. Rebertus and Burns (1997) examined the importance of gaps in woodland and savanna—communities where the frequency of fires overrides the importance of gaps. We hypothesize that in closed canopy forests, where fire occurs with varying frequency, wind-driven gap dynamics can control recruitment and ultimately stand composition and structure. We also hypothesize that the importance of gap dynamics varies with topographic position.

In this paper we aim to reveal the importance of disturbance that results in gap formation in Ozark forests. Specifically, we document the disturbance patterns associated with long temporal scales by using dendroecological methods and quantifying release events in growth of shortleaf pine and white oak. The objectives of this study were to (1) identify growth release events using remnant shortleaf pine and overstory shortleaf pine and white oak, (2) analyze the temporal variation of canopy disturbances among sites, (3) examine how topographic variation affects disturbance, and (4) note growth releases that occur during and subsequent to selected drought events.

STUDY SITES

Study sites were located at Pioneer Forest, LLC (L-A-D Foundation, St. Louis, MO), which uses single-tree selection for timber management. Pioneer Forest is a privately owned forest of nearly 65,000 ha located across six counties in the Missouri Ozark Highlands (Iffrig et al. 2004). We selected two sites at Pioneer Forest in Shannon County, MO: Mill Hollow/Current River Natural Area (MH/CRNA) (approximately 37°24' N, 91°26' W) and Randolph Tract/Woods Hole (RT/WH) (approximately 37°25' N, 91°38'W). Both sites are located in the Current River watershed and contain the three components for our study:

1) remnant shortleaf pine
2) dominant and codominant shortleaf pine and white oak >30 cm diameter at breast height (d.b.h.)
3) opposing slopes (south-facing vs. north-facing) along the same ridge

Mill Hollow includes a forested area of approximately 165 ha and is a generally south-facing slope ($\bar{x}$ =180.56° S) located on the east side of the Current River. Canopy dominant and codominant tree species in MH include scarlet oak (*Quercus coccinea* Muenchh.), white oak, and shortleaf pine. The Current River Natural Area is a forest of approximately 4 ha along a north-facing slope ($\bar{x}$=337.38° NNW) located on the same ridge as MH. Canopy dominant and codominant species in CRNA include white oak, black oak (*Quercus velutina* Lam.), and northern red oak (*Quercus rubra* L.). Elevations in MH/CRNA range from 1,100 m along the ridge top to 725 m at the lower slope positions. Randolph Tract/Woods Hole, a forest of approximately 497 ha on a generally SSW-facing slope ($\bar{x}$ =202.73°) located on the west side of the Current River, contains dominant and codominant white oak, shortleaf pine, black gum (*Nyssa sylvatica* Marsh.), and hickory (*Carya* spp.). Elevation transitions in RT/WH from 1,000 m at the upper slope positions to 650 m adjacent to the Current River.

METHODS

Sampling at MH and RT/WH occurred during the summers of 2009 and 2010. Belt transects (50 m x 100 m) were placed at upper slope and ridge top positions that were oriented with the slope contour at MH (15 transects) and RT/WH (18 transects). Within each belt transect, basal increment cores (one per tree) were sampled from shortleaf pine and white oak trees that were ≥30 cm d.b.h. Increment cores were sampled parallel with the slope contour to minimize the effect of reaction wood on the upper and lower portions of the stem. Remnant shortleaf pine stumps and natural snags were identified within each belt transect and cross-sections were sampled at ground level using a chainsaw. Universal Transverse Mercator coordinates (zone 15N) were collected for all increment cores and cross-sections using a handheld Garmin GPS (Olathe, KS). Tree-ring measurements for previously sampled white oak cores from CRNA were accessed via the International Tree-Ring Database (National Climatic Data Center 2009a-d).

Increment cores and cross-sections were sanded with progressively finer sandpaper (up to 1,200 grit) to differentiate smaller tree-rings (Stokes and Smiley 1996). Tree-ring width measurements to the nearest 0.01 mm for all samples were taken using a Velmex measuring stage (Velmex, Inc., Bloomfield, NY) and binocular microscope. Standard visual cross dating procedures (Yamaguchi 1991) and the COFECHA quality control program (Grissino-Mayer 2001, Holmes 1983) were used to cross date and verify the appropriate calendar year for each tree-ring.

We applied the percent growth change analysis (Nowacki and Abrams 1997) using 10-year running means to identify growth releases (a proxy for canopy disturbance) for each sample's tree-ring width chronology. The percent growth change (PGC) is determined by:

$$PGC = \frac{\bar{x}_2 - \bar{x}_1}{\bar{x}_1} \times 100 \qquad (1)$$

where $\bar{x}_1$ indicates the prior mean radial growth rate and $\bar{x}_2$ represents the subsequent mean radial growth rate. We categorized growth release events as minor (≥25 percent but < 50 percent), moderate (≥50 percent but <100 percent), and major (≥100 percent) to identify differences in patterns and the magnitude of release events given the limited availability of previous research on historic canopy disturbance in the Missouri Ozarks.

We compared periods of growth releases in shortleaf pine and white oak to periods of prolonged drought at the two sites to determine if trees were exhibiting a response following a stress. We calculated the mean reconstructed Palmer Drought Severity Indices (PDSI, Palmer 1965) for two stations in southern Missouri (Station 210: 37°5' N, 90°0' W; and Station 201: 37°5' N, 92°5' W) to identify historic prolonged droughts given that our sites were nearly equal distance between the two stations. We defined a prolonged drought as one in which the mean PDSI was <-2.0 for 2 or more consecutive years. In addition, we also compared prolonged drought events to growth release events with the potential of growth releases occurring during and up to 5 years following the end of a drought. However, we differ from others (Rubino and McCarthy 2000) in that we identified consecutive years of drought in which the mean PDSI ≤-2.0. The results were nine drought events between 1700 and 2000 with $\bar{x}$ ≤-2.0 and lasting for at least 2 years (Table 1). Pinpointing those releases that occurred following a drought allowed us to infer releases that occurred at times other than drought that may indicate other types of canopy disturbance (ice storms, logging, windstorms, defoliation events).

Table 1.—Comparison of known drought years from mean reconstructed PDSI to the number of shortleaf pine and white oak combined releases across MH/CRNA and RT/WH; percentage of samples that released is based on the total number of shortleaf pine and white oak samples from both study sites during and up to 5 years following the drought period

Drought years (mean PDSI)	Number of shortleaf pine releases	Number of white oak releases	Percentage of samples that released (%)
1703-1705 (-2.091)	3	2	21.7
1734-1738 (-2.372)	3	7	19.6
1771-1774 (-2.329)	13	13	35.6
1799-1801 (-3.525)	10	3	15.9
1834-1835 (-3.210)	3	1	4.2
1838-1839 (-3.156)	17	5	22.7
1855-1860 (-2.124)	9	17	25.7
1952-1954 (-2.692)	17	24	22.2
1963-1964 (-2.359)	5	9	6.1

RESULTS

Growth Release Analysis

Increment cores and remnant wood of shortleaf pine (n = 52) and increment cores of white oak (n = 49) were collected from MH, and 55 white oak ring-width chronologies were used from CRNA (National Climatic Data Center 2009a-d) to analyze for growth releases. Ring-width measurements and cross-dating resulted in a 339-year ring-width chronology for shortleaf pine (1670-2009) and a 172-year ring-width chronology for white oak (1836-2008) from MH. A 404-year ring-width chronology (1588-1992) was used for growth release analysis from CRNA. A total of 60 shortleaf pine and 56 white oak increment cores were sampled from RT/WH, resulting in a 244-year ring-width chronology for shortleaf pine (1765-2009) and a 214-year ring-width chronology for white oak (1795-2009).

Mill Hollow/Current River NA

Mill Hollow trees experienced a total of 223 release events (n_{pine} = 166; $n_{white\ oak}$ = 57) from 1670 to 2009. The greatest number of releases in MH were moderate (>50 percent but <100 percent) (n = 83). Taking into account all categories of releases, there were historic synchronous shortleaf pine releases in MH based on the percentage of samples that released during the timeframe 1754-1760 (45 percent of samples), 1773-1776 (46 percent), 1800-1810 (81 percent), and 1840-1845 (80 percent). A large contemporary release occurred in MH shortleaf pine in 1985-1990 (88 percent). Thirty-six percent of white oak in MH experienced a release during the same time period (1980-1990) as the contemporary shortleaf pine. The earliest growth release in MH was in 1706.

White oak at CRNA had a total of 216 release events across the respective ring-width chronologies. In comparison to MH, the greatest number of releases for white oak at CRNA were minor (>25 percent but <50 percent) (n =114). White oak in CRNA experienced synchronous releases in 1730-1740 (51 percent of samples) and 1775-1785 (46 percent). The earliest detected release from CRNA was in 1611 (Fig. 1).

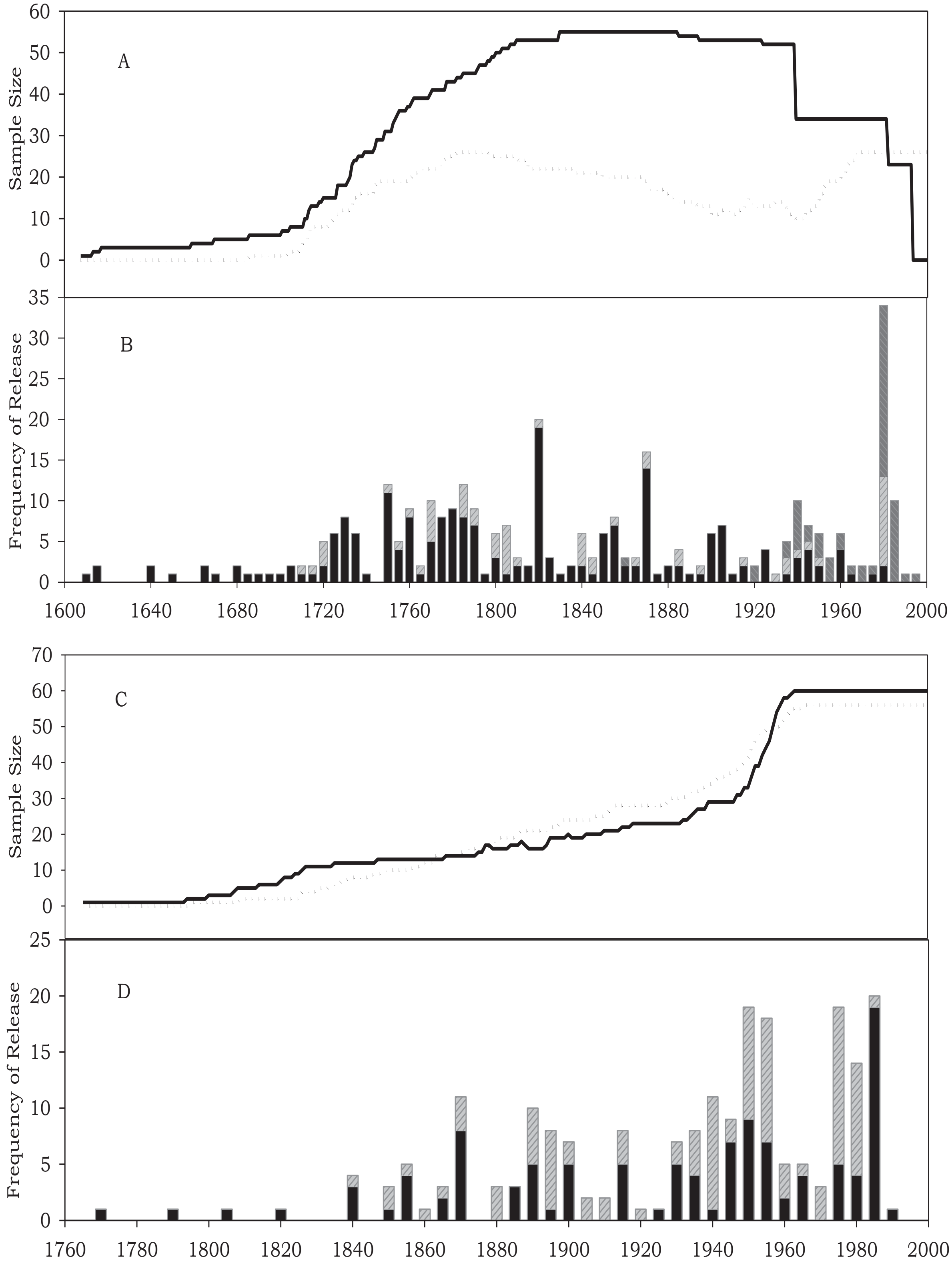

Figure 1.—Frequency of growth releases in MH/CRNA (1588-2009) and RT/WH (1765-2009). (A) Sample size from MH/CRNA. Black = CRNA; Dotted = MH. (B) Number of releases every 5 years in MH/CRNA. Black bars = CRNA white oak; Light gray = MH pine; Dark gray = MH white oak. (C) Sample size from RT/WH. Black line = shortleaf pine; Dotted line = white oak. (D) Number of releases every 5 years at RT/WH. Black bars = shortleaf pine; Dark gray = white oak. Note differences in scale.

All but one remnant shortleaf pine exhibited at least one growth release in 1670-1935, but 38 percent of living shortleaf pine ($\bar{x}_{age}$=71.3 years, S.E. = 4.2) in MH did not exhibit a growth release in 1899-2009. Approximately 60 percent of white oak ($\bar{x}_{age}$=67.0 years, S.E. = 3.5) in MH did not exhibit a growth release in 1836-2009. White oak samples from CRNA also had a large number of trees that did not release (29 percent) in 1588-1992.

A comparison of MH and CRNA is appropriate given that these two sites were on the same ridge but opposite slope positions. One notable release event occurred concurrently on both slopes from 1773 to 1785. Releases in CRNA were more commonly minor events; releases of shortleaf pine and white oak in MH were more commonly moderate to major releases based on our release categories.

Randolph Tract/Woods Hole

The tree-ring record of shortleaf pine in RT/WH revealed 109 growth release events with the earliest occurring in 1775. White oak in RT/WH experienced 105 growth release events; the first detected release occurred in 1842 (Fig. 1). Fifty-three percent of shortleaf pine and 18 percent of white oak demonstrated a synchronous release during 1872 to 1875. From 1947 to 1957, 40 percent of shortleaf pine and 28 percent of white oak released. The distribution of releases based on category (minor, moderate, major) were evenly distributed for shortleaf pine; white oak in RT/WH experienced more moderate releases (n = 40).

Comparison of Droughts and Growth Releases

We calculated the mean reconstructed PDSI (1588-2003) to compare growth releases to known periods of drought (Fig. 2). We identified years in which mean PDSI values were ≤-2.0, and there were negative PDSI values immediately before and after the year in which the reconstructed PDSI value was ≤-2.0. Due to the limited sample size during the 1600s, we restricted our analysis to the period 1700 to 2000.Using known drought years, we identified growth releases that were coincident with or immediately subsequent to the last year of identified drought (Table 1). As the sample size increases, we found that some release events corresponded during and subsequent to the identified drought period (Fig. 2).

Most release events during the identified prolonged drought periods were minor or moderate in growth response across both sites. However, two of the periods of drought (1771-1774; 1952-1954) had 10 and 18, respectively, releases that were categorized as major events (≥100 percent release). In addition, 14 of the major releases during the 1952-1954 drought period occurred at RT/WH. Of the major releases during the 1771-1774 drought period, all occurred in MH/CRNA.

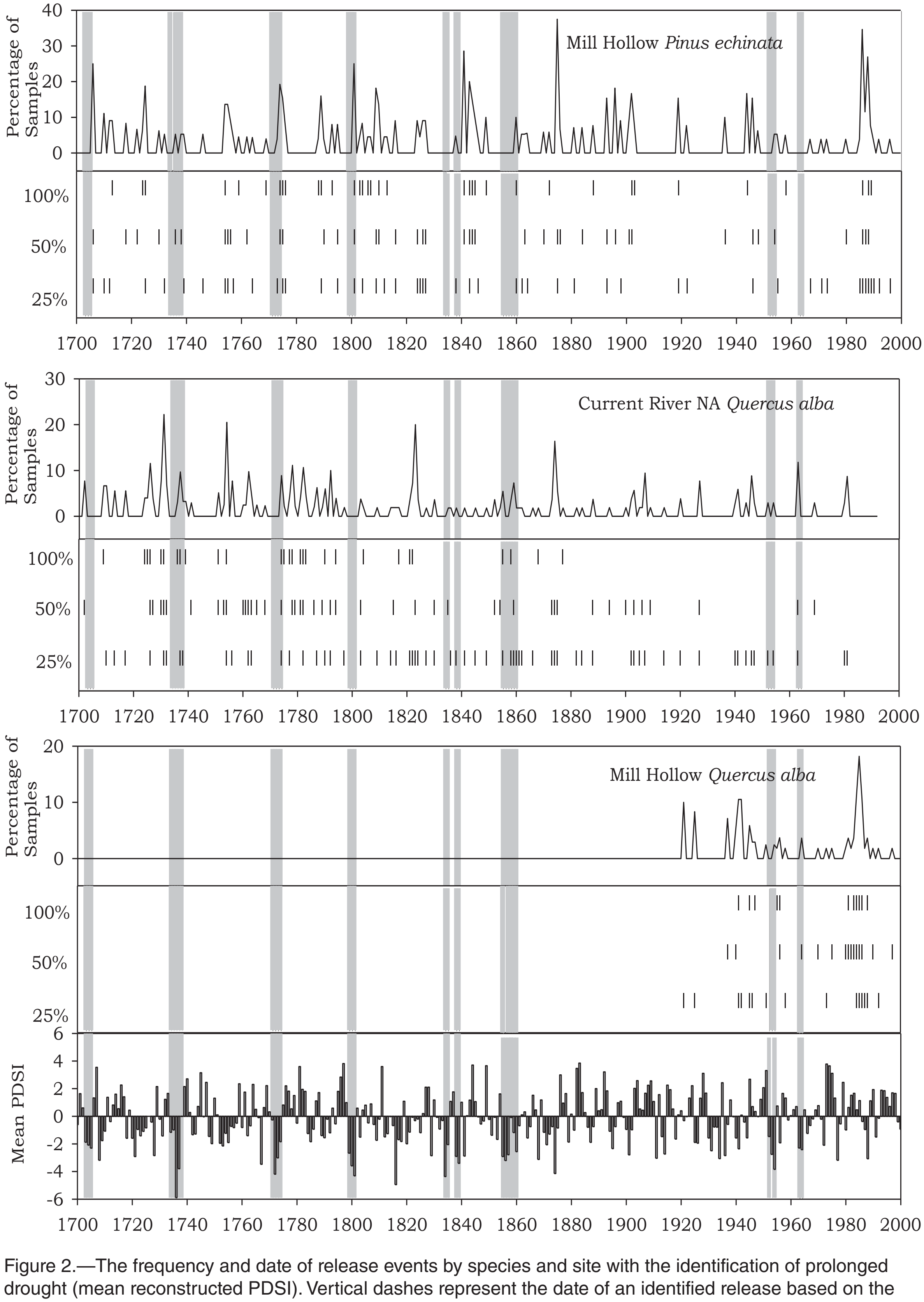

Figure 2.—The frequency and date of release events by species and site with the identification of prolonged drought (mean reconstructed PDSI). Vertical dashes represent the date of an identified release based on the percent increase in growth rate (25 percent = >25 percent but < 50 percent; 50 percent = >50 percent but <100 percent; 100 percent = >100 percent). The percentage of samples that released per year is shown. The gray shaded area represents the identified prolonged drought events ($\bar{x}$ = <-2.000). Note differences in the length of chronologies between MH/CRNA and RT/WH. (Figure 2 continued on page 57.)

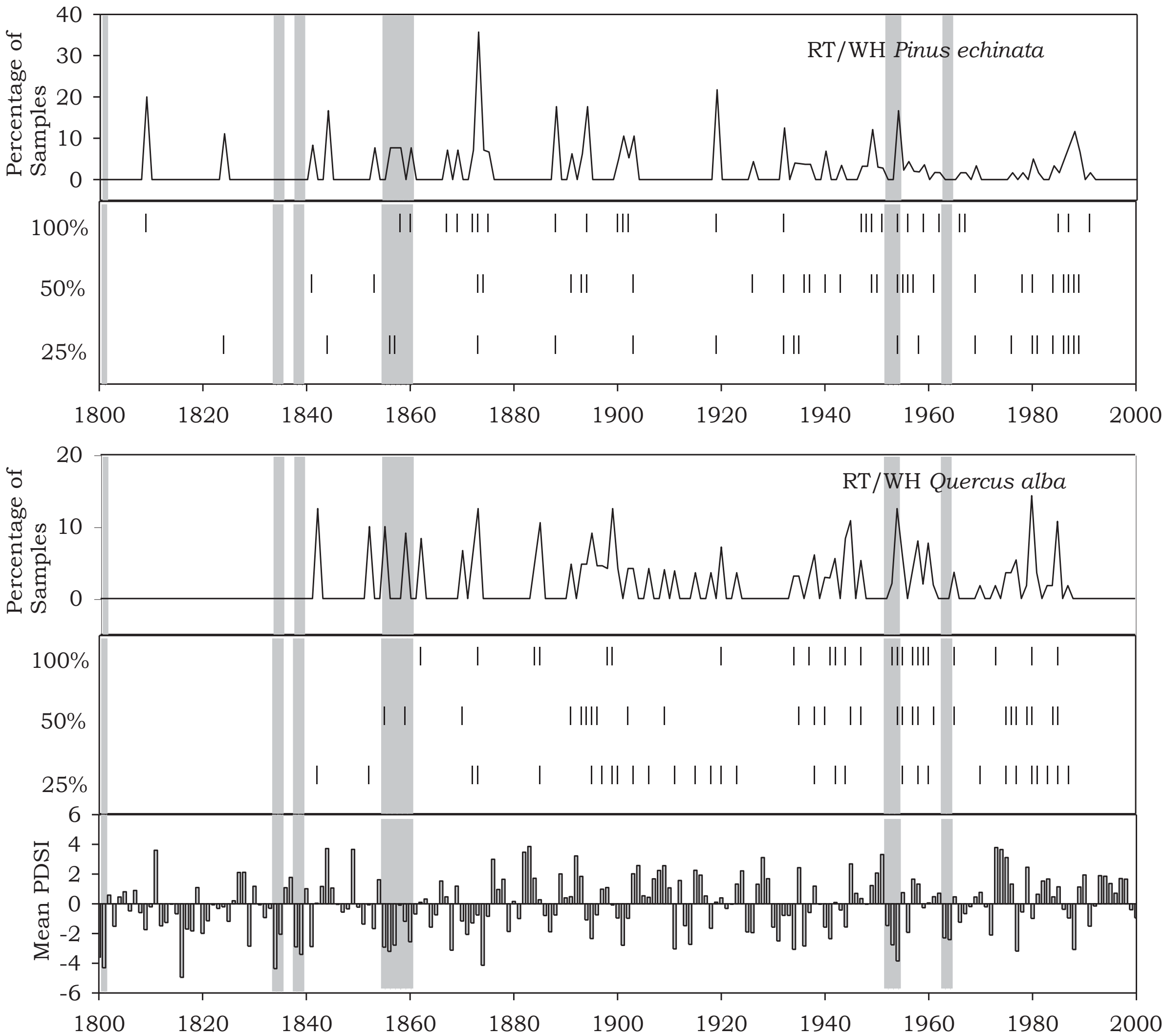

Figure 2.—continued from page 56.

DISCUSSION

Disturbance History

To facilitate an interpretation of the disturbance history of our study sites, we divided the analysis of growth releases into three centuries that encompass the temporal range of our dataset. Each century demonstrates variability in the frequency and magnitude of disturbance. The discussion of disturbance history focuses on the period 1700 to 2000 because of the limited sample size before 1700.

1700 – 1800

During this century, Mill Hollow shortleaf pine had 52 release events and white oak in CRNA had 90 releases with most of the releases concentrated during 1770-1800 (42 percent of all releases). The oldest shortleaf pine sample from RT/WH also released during the late 18th century. Our data suggest that some of the releases from 1770 to 1780 may have been associated with a drought (Table 1). However, in a study of historic anthropogenic fire regimes in the Missouri Ozarks, Guyette et al. (2002) indicated a potential increase in eastern Native American activity as tribes were displaced to the west and into the Missouri Ozarks during this time period. A study of the historic culture of the Current River watershed, where our two study sites are located, suggests the presence of Native American tribes adjacent to the Current and Jacks Fork Rivers (Stevens 1991). The concentrated release events may be attributable to these tribes using the forest resource along the Current River watershed.

1800 – 1900

The number of detected releases increased in MH/CRNA during this century (144 release events). One would expect an increased likelihood of detecting release events as sample size increases, but sample size in MH/CRNA decreased in 1799-1899 from 77 to 66. A total of 51 release events were detected in RT/WH. Most of the historic release data for RT/WH were concentrated during this century.

Patterns emerge from the release data for our two study sites during the19th century (Fig. 1). A large number of shortleaf pine samples (n=18) from MH indicate a major release in 1800-1809. However, during this same period, only four white oaks from CRNA exhibited a release. A small number of shortleaf pine samples released during and immediately subsequent to a drought from MH and RT/WH (Table 1). In addition, fire scar data indicate a fire during 1800 (King, unpublished data). Based on GPS point data, releases during 1800-1810 cover approximately 0.8 km at the upper slope position in MH. Our data suggest a volatile time in terms of disturbance in Mill Hollow during the late 18th and early 19th century.

Another group of major releases in MH appears during the 1840s, and then at least one shortleaf pine released every decade from 1850 to 1900. A small number of white oak samples from CRNA show major releases in 1845-1860. Several Euro-American settlements had already been established before 1850 north and south of the present-day study sites (Stevens 1991). The growth releases likely reflect the moderate clearing of the forest associated with these settlements. Most release events in white oak from CRNA were minor to moderate in growth, likely indicating that these trees had attained canopy status by 1860 to 1900. The minor and moderate releases in CRNA white oak may reflect canopy dieback of neighboring trees. In addition, only two major releases were detected in CRNA white oak during the middle and late 19th century.

Release events in RT/WH indicate an increase in the number of growth releases between 1865 and 1900 for both white oak and shortleaf pine, particularly during the last 20 years of the 19th century (Fig. 1) which may be attributable to the influx of the logging industry and Euro-American population during that time (Stevens 1991).

1900 – 2000

Evidence from these data indicates a limited number of shortleaf pine samples that date to the early 20th century (Fig. 1), particularly in MH. High fire frequencies during the late 19th and early 20th century, along with livestock disturbance (Guyette et al. 2002, 2003), may have contributed to the decreased establishment of shortleaf pine during this period. This is supported by the lagged establishment of the current shortleaf pine cohort ($\bar{x}_{age}$=71.3 years, S.E. = 4.2).

A large release event appeared to occur during the 1945-1955 period in RT/WH. During that period, a small number of releases occurred in MH but are noticeably absent in CRNA. Before Pioneer Forest took over ownership, the forest in the study sites was managed for white oak staves. Lands were sold to Pioneer Forest in the early 1950s (Iffrig et al. 2004). These releases, particularly in RT/WH, may reflect harvesting by previous owners.

Few trees at both sites released between 1960 and 1980. Individual tree releases that did occur during this time may reflect responses to small gap formations in the canopy. Release events appeared to occur at both sites in shortleaf pine and white oak between 1980 and 1990, possibly associated with harvests by Pioneer Forest.

Drought and Release Events

Some release events at both study sites appear to be associated with periods of drought. However, generally few trees during and subsequent to the droughts had a growth release. Our data indicate that the magnitude of historic releases during and subsequent to the identified prolonged droughts ranged widely from minor to major releases. Minor releases may reflect partial crown dieback, or in the case of major releases, the death of an adjacent overstory tree. Regardless, releases during and subsequent to droughts tended to result in few trees demonstrating a release. It is possible that releases that occurred during a prolonged drought period may not be due to the drought conditions. However, releases that occurred a few years following the drought (2-6 years) may be related to reduced growth during the period of drought (Orwig and Abrams 1997). Rubino and McCarthy (2000), in their drought analysis of white oak, determined that white oak exhibited a growth decline up to 5 years following a severe drought (PDSI = -5.23). Within our identified drought periods were 4 years in which PDSI < -4.0 (1736, 1772, 1801, 1834). The result was the detection of growth releases during and subsequent to the drought periods that may be directly or indirectly attributable to drought events in the Missouri Ozarks.

Given the relative proximity of both study sites, we can assume that prolonged drought conditions had a similar effect on shortleaf pine and white oak. By taking into account drought as a contributing disturbance to a forest, it may be possible to infer causation of growth releases when there is limited availability of historical documentation. A contemporary example from our study is the prolonged drought during 1952 to 1954 in which there are differences in the number of growth releases between MH/CRNA and RT/WH (Fig. 2). There are two potential explanations for this variation. One explanation may be the occurrence of at least one management harvest at RT/WH during this period, which may reflect the large number of release events subsequent to the prolonged drought, yet we do not identify the same degree of release at MH/CRNA. Secondly, a large mortality event may have contributed to release events. However, we cannot infer causation of the disturbance at the tree level given the potential of multiple disturbances (harvest, mortality, drought) occurring at the same time. If there is a lag between the disturbance and growth release (D'Amato and Orwig 2008, Jones et al. 2009), it is possible the disturbance (timber harvest) occurred just before the drought.

CONCLUSIONS

Both sites indicate periods of synchronous release events, likely indicating large gap formations due to anthropogenic influence or a natural disturbance such as windstorms. There are also indications of responses to small gap formation in which an individual tree was released during a decade throughout the disturbance chronologies from both sites. The only exception was during the 1980s in which a large number of trees revealed a release, which we hypothesize to be related to management harvests at the two sites. Throughout the last 400 years, these two sites have exhibited periods of high frequency canopy disturbance. However, each site revealed differences in the timing of large-scale canopy disturbance, particularly before 1900. Subsequent to 1900, both sites exhibit similar patterns of release culminating in a large number of releases during the 1940s through the 1950s and the 1980s, suggesting the development of timber management. Prolonged drought events may have contributed to lagged growth releases in some of the trees at the two sites. We encourage further analysis of drought in forests to better evaluate causation of historic disturbance when there is limited historical documentation to validate disturbance type.

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NINE-YEAR PERFORMANCE OF FOUR HARDWOODS ON A HARVESTED SITE WITH AND WITHOUT FERTILIZER, TREE SHELTERS, AND WEED MATS IN SOUTHERN ILLINOIS

Felix Ponder, Jr. and J.W. Van Sambeek[1]

Abstract.—Quality hardwood species often dominate stands on intermediate to high quality sites before regeneration. However, successfully regenerating these species after the harvest is rarely achieved on these sites. Hardwood species were planted on a high quality site in southern Illinois after clearcutting to study the effect of several cultural practices on the hardwoods' survival and growth. The performance of four hardwoods, black walnut (*Juglans nigra* L.), northern red oak (*Quercus rubra* L.), white oak (*Q. alba* L.), and cherrybark oak (*Q. pagoda* Raf.), were significantly ($\alpha = 0.05$) affected by slow-release fertilization, tree shelters, and weed mats at age 9. Survival of all species was higher when treated with 10 g of slow-release fertilizer (16-6-8 NPK) in the planting hole than when not treated. Also, survival was better for trees enclosed in shelters than for trees not enclosed in shelters. Tree survival decreased with the use of weed mats. Tree shelters improved ninth-year height growth of northern red oak, white oak, and cherrybark oak, but not black walnut. The total height growth of black walnut, white oak, and cherrybark oak was greater with fertilizer at planting than without fertilizer packets. The height of red oak was less with fertilizer than without fertilizer. Trees with weed mats were shorter and had less height growth than trees without them.

INTRODUCTION

After decades of research describing techniques for successful regeneration of central hardwood forests, regenerating desirable hardwoods such as oaks after clearcutting continues to be a problem on many sites in the region. There have been various explanations why oaks are being replaced by less desirable species over much of the region (Heitzman and Grell 2003). Most silviculturists agree that, especially on more mesic sites, shade-tolerant non-oak species accumulate beneath undisturbed mature oak forests and eventually recruit into the overstory following disturbances such as timber harvesting (Johnson 1993, Johnson et al. 2009, Larsen and Johnson 1998).

However, even on sites with many desirable species including oak and black walnut in the understory, regeneration success after clearcutting can still be limited by stem size, vegetative competition, and site quality (Johnson 1993, Sander et al. 1984). A survey of 5- to 26-year-old clearcut oak stands found that on poor sites (oak site index 50-59) upland oaks became increasingly more abundant with stand age and accounted for 64 percent of all stems in all stands 15 years old and older. On medium sites (oak site index 60-69), the oaks obtained moderate importance after clearcutting and changed little with increasing stand age. On good sites (oak site index 70-80), dominant and codominant oaks decreased with time and accounted for only 11 percent of stems in stands 15 years old and older (Hilt 1985). Similar results were observed by Groninger and Long (2008) for sloping landscapes and differences in aspect. They found that the abundance of oaks increased from lower (moist) to upper (drier) slope positions and from cool (north-east) to hot (south-west) aspects.

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Planting nursery stock on harvested sites, especially on sites that lack adequate advance regeneration, and in small openings is an alternative (Demchik and Sharpe 1999, Heitzman and Grell 2003, Ponder 1995). The success of planted trees has been shown to be increased by competition control and proper site-species match. Results of studies incorporating tree shelters have been mixed; some indicated a positive influence on growth (Ponder 2003, Teclaw and Isebrands 1991) and others did not (Lantagne 1996, Teclaw and Zasada 1996). Because of vegetative competition, broadcast fertilization at the time of planting is usually discouraged.

An inventory of the understory in a southern Illinois stand scheduled to be clearcut showed that the vast majority of the reproduction consisted of hardwood species not considered desirable for timber or wildlife production. The site was rated as good (oak site index 80+) (Carmean and Hahn 1983), suggesting a difficulty in regenerating desirable overstory species given the limited number of advance regeneration stems present. The objective of this study was to compare the long-term survival and growth of planted black walnut (*Juglan nigra* L.), northern red oak (*Quercus rubra* L.), white oak *Q. alba* L.), and cherrybark oak (*Q. pagoda* Raf.) subject to fertilization, tree shelter, and weed mat treatments.

STUDY AREA

The study site is located on a gently rolling landform with slopes less than 8 percent and dissected by intermittent drainage channels. Current land conservation measures minimize water movement over the study area. The soil is a deep (solum thickness > 160 cm), well-drained Alford silt loam (fine-silty, mixed mesic Typic Hapludalfs) with a surface pH of 6.2, and P, K, Ca, and Mg in amounts of 55, 151, 1850, and 168 mg kg^{-1}, respectively. Before the stand was clearcut, maple (*Acer saccharum* Marsh.) and beech (*Fagus grandifolia* Ehrh.) were the most prevalent species based on basal area, together occupying 55 percent of the basal area. Hickory (*Carya* spp.), black walnut, and sweetgum (*Liquidambar styraciflua* L.) combined occupied 35 percent and oaks including northern red oak, white oak, and black oak (*Q. velutina* Lam.) occupied 10 percent of the basal area.

METHODS

Following the timber harvest in spring 1992, all remaining vegetation including trees, tree tops and branches, shrubs, and grapevines (*Vitis* spp.) were removed manually. Vegetation was cut with a chain saw or long-handle pruner and carried off plots by hand. Stumps were not sprayed to prevent sprouting. No other site preparation was done until 4 years later when the forest floor vegetation was sufficient to support a prescribed fire to reduce undesirable woody competition (Miller 1993). No estimate of species present was made before burning. Following the midday spring burn, the site was planted manually to 1-year-old nursery-grown black walnut, northern red oak, white oak, and cherrybark oak seedlings from the George O. White State Nursery in Licking, MO. Before planting, all seedlings less than 6 mm in diameter at root collar were culled from the planting stock. Root systems were clipped to 20 cm. Seedlings were planted in rows 2.4 m apart and 1.8 m apart within rows. Treatments included (1) two levels of fertilization, with and without prepackaged slow-release fertilizer; (2) two levels of tree shelters, with and without tree shelter; and (3) two levels of weed mats, with and without weed mats. Treatments were arranged in a randomized block design. Each of three blocks consisted of four tree species x eight treatments x 8 to 10 seedlings in row plots. At the time of planting, the slow-release fertilizer (16N-6P-8K) packet (Right Start®, TREESSENTIALS, St. Paul,

Table 1.—Ninth-year survival of four hardwood tree species planted in a southern Illinois clearcut forest in treatments at time of planting consisting of with and without slow-release fertilizer applied to the planting hole, with and without tree shelters, and with and without weed mat placed around seedlings

Treatment	Tree species			
	Black walnut	Red oak[†]	White oak	Cherrybark oak
	Percent survival			
Fertilizer				
With	61a[±]	60a	61a	73a
Without	67a	46b	47b	66a
Tree shelter				
With	65a	68a	64a	89a
Without	58a	51b	48b	59b
Weed mat				
With	57a	40a	48a	59a
Without	74b	65b	59b	72b

[†]Northern red oak

[±]Numbers with the same letter for different levels of a treatment for a tree species are not significantly different at $P \leq 0.05$.

MN) was placed in the bottom of the planting hole before the seedlings. Vispore® weed mats, a light weight, black polyethylene plastic, 0.9 x 0.9 m in size, were placed around seedlings receiving the treatment and anchored with soil and 15-cm-long metal pins. Tree shelters (TREESSENTIALS, St. Paul, MN) were 1.2 m tall and ranged from 7.6 to 10.2 cm in diameter. They were attached to 1.3-cm-diameter metal conduit placed near seedlings and held in place with plastic tie bands. For the first 2 years after planting, 61-cm-wide strips on both sides of rows were sprayed in the spring with a mixture of glyphosate (227 ml) and simazine (100 g) in 11 L of water using a backpack sprayer to control weeds in all treatments. Stump sprouts between rows were also sprayed with this herbicide mixture.

Over 9 years, tree survival and growth were measured periodically and at age 9. The experiment was analyzed as a randomized complete block design. Survival was analyzed using the PROC LIFETEST procedure (Allison 1995). Growth data were analyzed using analysis of variance with the PROC GLM procedures in SAS Version 8.2 (SAS Institute, Cary, NC). All statistical tests were performed at the $\alpha = 0.05$ level of significance.

RESULTS

After 9 years, survival of northern red oak and white oak was better with slow-release fertilization at planting than without it (Table 1). Survival for all oaks was better with tree shelters than without tree shelters. Weed mats tended to lower survival for all species, reducing survival to less than half for red and white oaks and more than two-thirds for black walnut and cherrybark oak (Table 1).

Except for northern red oak, fertilized trees had more height growth than unfertilized trees with differences of 1.5, 0.7, and 0.6 m for black walnut, white oak, and cherrybark oak, respectively (Table 2). Fertilizer was negatively correlated with northern red oak height growth with fertilized trees averaging less than 0.6 m in height growth over 9 years. Only the height growth of northern red oak and cherrybark oak were better with tree shelters than without tree shelters. Weed mats decreased height growth significantly only for white oak.

Table 2.—Total height growth for four hardwoods in southern Illinois planted in an upland forest clearcut after 9 years with and without slow-release fertilizer, tree shelter, and weed mat at planting

Treatment	Black Walnut	Red oak†	White oak	Cherrybark oak
	---------- Meters ----------			
Fertilizer				
With	8.25a±	2.98a	2.59a	4.42a
Without	6.76b	3.61b	1.94b	3.87b
Tree shelter				
With	7.44a	4.02a	2.72a	4.72a
Without	7.13a	3.30b	1.96a	3.86b
Weed mat				
With	6.75a	3.17a	1.74a	3.80a
Without	7.56a	3.45a	2.71b	4.32a

†Northern red oak

±Values with different letter for a treatment are significantly different according to Tukey multiple range test.

DISCUSSION

After 9 years, slow-release fertilization at the time of planting increased survival for all three oak species, but it did not increase the survival of black walnut (Table 1). Because newly planted bareroot seedlings do not have well-established root systems, they generally undergo moisture and nutrient stress before they become established. Apparently, *Quercus* species are more tolerant of moisture stress (Leuschner et al. 2001) than black walnut. Fertilization, on the other hand, may have reduced nutrient stress associated with bareroot seedlings by stimulating root development and initiating shoot growth sooner (Burdett et al. 1984) thus increasing survival and reducing the establishment period (Brockley 1988). Earlier, Burdett et al. (1984) reported that an application of slow release N, P, and K fertilizer at planting improved shoot growth of bareroot spruce (*Picea glauca* (Moench) Voss) trees more in the second season than in the first, while container-grown stock made large shoot growth responses during the first and second seasons. In contrast to the oaks, although not significantly different between treatments, fewer black walnuts survived with fertilization than without it. Williams (1974) reported that the addition of 28 g of conventional 8N-32P-8K analysis fertilizer at planting and an additional 57 g broadcast in a cultivated circle around each tree 1 month later reduced survival and growth of black walnut. The author (Williams 1974) attributed the negative effect to not controlling the overtopping vegetation that was vigorously stimulated by fertilizer or to damage to seedling roots by coming in contact with fertilizer in the planting hole. In another black walnut fertilization study using slow-release fertilizer, Jacobs et al. (2005) reported that survival was not affected and remained above 85 percent for treatments with and without fertilization 2 years after planting.

The height growth response of trees to fertilization was inconsistent among the oaks (Table 2). Although height growth for black walnut, white oak, and cherrybark oak increased with fertilization, it was the opposite for fertilized northern red oak. Reports in the literature indicate the inconsistent response of young black walnut to fertilization (Jacobs et al. 2005, Nicodemus 2008, Ponder 1994, Williams 1974), but much less information is available on young oaks. One reason may be that fewer oak plantations are being established in old fields compared to black walnut. Most forest soils, while probably not optimal in nutrient composition for tree growth, do have nutrient capital to support tree growth at some acceptable rate, with the greatest gains in growth coming from weed control (Johnson et al. 2009). However, the reason for the lower height growth of fertilized red oaks compared to the better height growth for unfertilized trees is not known.

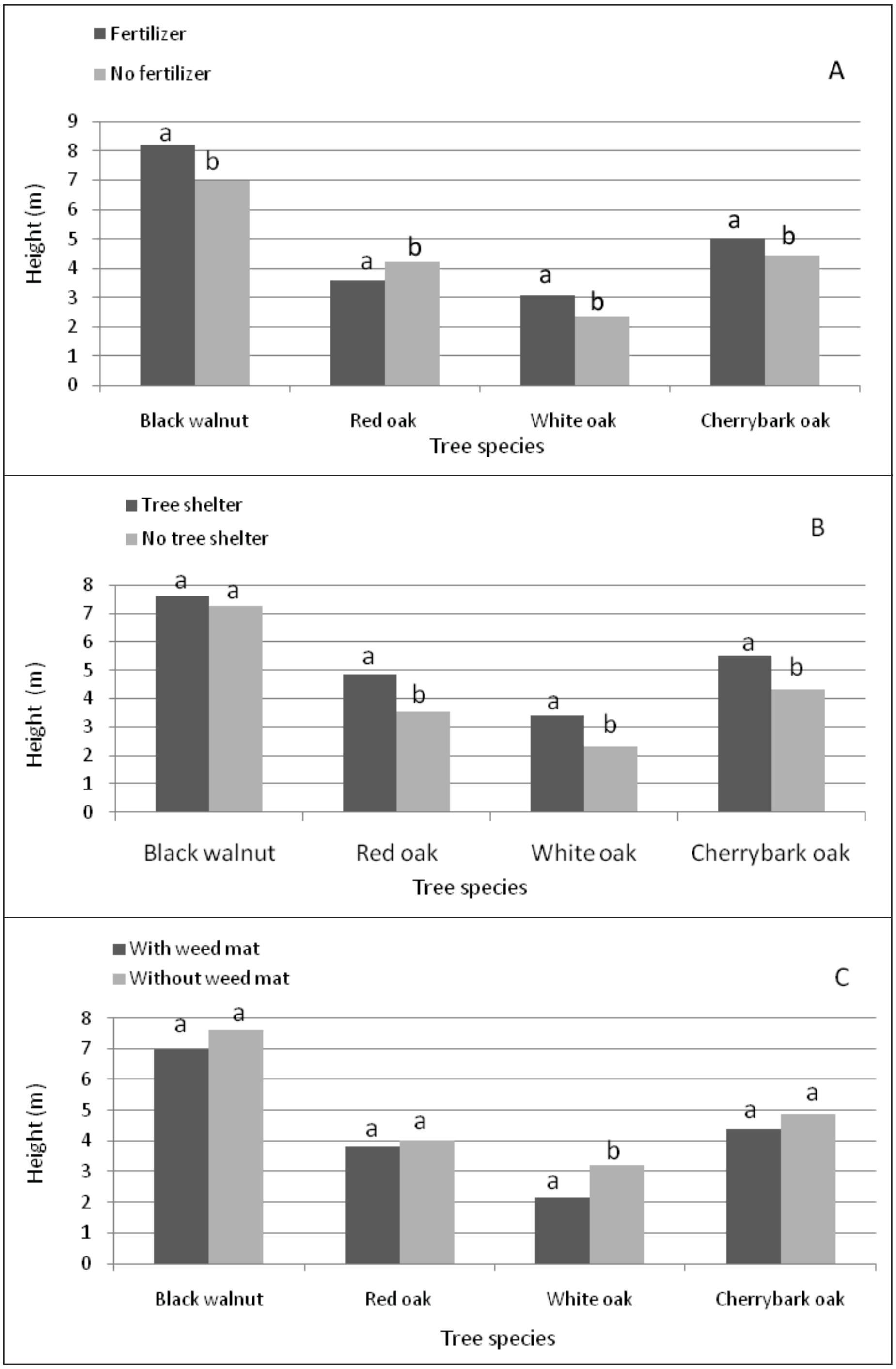

Figure 1.—Nine year height of black walnut, northern red oak, white oak, and cherrybark oak (A) with and without slow-release fertilizer, (B) with and without tree shelter, and (C) with and without weed mat. Values with different letter for a treatment are significantly different according to Tukey's multiple range test.

Both height and height growth of all species of seedlings benefited from the use of tree shelters (Table 2, Fig. 1). But differences were not significant for black walnut and white oak. Better height and height growth with tree shelters than without them as demonstrated by northern red oak and cherrybark oak is not unusual (Bardon and Countryman 1993, Gillespie et al. 1996). Neither is the insignificant height growth response in black walnut and white oak (Lantagne 1996, Lantagne and Miller 1997). Mechanisms for these responses are not fully understood. Aside from protecting trees from animals and mechanical dangers, growth enhancement attributed to tree shelters is likely due to increased air temperature, CO_2, and reduced wind inside the shelter (Puértolas et al. 2010). These enhanced conditions tend to favor seedling survival and growth.

Weed mats were not beneficial for tree survival or tree growth (Table 2). The reason for the poor performance of weed mats on tree growth is not known. It may be due to rodent damage as they may live, feed, and nest beneath mats, thus causing death and damage to seedlings (http://www.cacaponinstitute.org/WVPTS/deerfence.htm). Although weed barriers were not effective in this study, they have many positive attributes including increasing soil temperatures in the spring, reducing evaporative soil moisture loss during dry periods, controlling herbaceous competition, and increasing survival and growth of young hardwood trees (Geyer 2003).

Two years of weed control likely influenced what plant species inhabited plots and reduced the number of some species that can regenerate by sprouting, increasing the opportunity for regeneration from seeds. Regenerating vegetation was not inventoried, but visually a major component of the regeneration consisted of yellow-poplar (*Liriodendron tulipifera* L.). It was not uncommon for planted trees and natural regeneration including yellow-poplar to be nearly the same height. However, the lack of post-treatment data on the composition of understory species and height keeps us from better understanding how treatment trees compete with trees from natural origin on this site.

In summary, slow-release fertilizer packets placed in the planting hole increased tree survival for two of the oak species but not for black walnut, while increasing height growth for all species except northern red oak. Tree shelters increased survival for all oaks, but height growth only for northern red oak and cherrybark oak. The use of weed mats reduced survival for all species and white oak height growth. Except for northern red oak in the weed mat treatment, survival at age 9 for the remaining species and treatments was 50 percent or higher, suggesting that a significant number of these species are continuing to be a part of the regenerating stand.

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WINTER INJURY OF AMERICAN CHESTNUT SEEDLINGS GROWN IN A COMMON GARDEN AT THE SPECIES' NORTHERN RANGE LIMIT

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Abstract.—Hybridization of American chestnut (*Castanea dentata*) with Chinese chestnut (*C. mollissima*), followed by backcrossing to American chestnut, is conducted to increase the resistance of resulting stock to chestnut blight, caused by the fungal pathogen *Cryphonectria parasitica* (Murr.) Barr. Backcross breeding is being used to restore American chestnut throughout its range, including cold high elevation sites in southern and central regions, and along chestnut's northern range limits. Until now, a comparative analysis of the growth and cold hardiness of American chestnut seed sources grown in cold environments had not been conducted. We assessed first-year growth and winter shoot injury (terminal shoot mortality that reduces apical dominance and results in a shrubby form) of American chestnut seedlings from 13 genetic sources: four southern, four central, and five northern seed sources, each representing one or more half-sib families, grown in a common garden in Vermont. No differences in height or diameter growth or in winter shoot injury attributable to the region of seed source origin were detected. However, significant differences in growth and winter injury were detected among sources within each region. There appeared to be a tradeoff between growth and winter injury: sources that had the greatest growth were generally the most vulnerable to winter shoot injury.

INTRODUCTION

American chestnut (*Castanea dentata* (Marsh.) Borkh.) was once a dominant tree species in much of eastern North America where it represented up to 40 percent of the forest canopy (Keever 1953) and as much as 50 percent of the forest canopy in the central Appalachians (Braun 1950, Russell 1987, Smith 2000). American chestnut was fast growing (diameter growth as great as 2.5 cm/yr) and large (e.g., reaching heights of 37 m and diameters of 1.5 m) (Buttrick 1925, Kuhlman 1978). Furthermore, the straight-grained, rot-resistant wood; abundant production of nutritious nuts; and high tannin content made American chestnut a species with high commercial value (Anagnostakis 1987, Rice et al. 1980). However, about one century ago, chestnut blight (caused by the fungus *Cryphonectria parasitica* (Murr.) Barr) was introduced to the United States (Griffin 2000). The girdling cankers produced by the pathogen led to widespread tree mortality and the functional removal of American chestnut as an overstory tree throughout its range (Griffin 2000). Considering the economic and ecological value American chestnut once provided, various strategies of species restoration have been attempted. One approach that shows promise for providing blight-resistant trees in the near future involves hybridizing American chestnut with blight-resistant Chinese chestnut (*Castanea mollissima* Blume) or Japanese chestnut (*Castanea crenata* Sieb. and Zuc.) and then successively backcrossing blight-resistant progeny with American chestnut to produce blight-

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resistant trees with approximately 94 percent American chestnut germplasm (The American Chestnut Foundation [TACF] 2010). Although this breeding tactic addresses the primary challenge to American chestnut survival and productivity rangewide, it does not address the selection of adaptive traits needed to tolerate localized stresses, such as tolerance to freezing, that could benefit trees growing in cold montane or northern locations.

Field measurements indicate that some genetic sources of American chestnut, and potentially blight-resistant backcross stock, are vulnerable to winter freezing injury and dieback of terminal shoots, which often leads to a bushy form when apical dominance is disrupted (Gurney et al. 2011). This injury has been noted from Virginia northward in various American chestnut breeding orchards (personal communications with TACF orchard managers). One prominent factor that can influence cold tolerance is the genetics of plant tissues (Aitken and Hannerz 2001, Balduman et al. 1999). In particular, temperature gradients associated with the latitude of source material typically result in predictable variations in species adaptation to the cold consistent with genetic adaptations to native temperature regimes (Aitken and Hannerz 2001). To evaluate the influence of genetics on the field performance of American chestnuts in a cold environment, we established a planting of 13 genetic sources of American chestnut on the Green Mountain National Forest (GMNF) in Leicester, VT, and assessed seedling growth and winter shoot injury after 1 year of out planting.

STUDY AREA

American chestnut seeds (nuts) were collected by volunteers and TACF staff. Nuts were collected in fall 2008 and kept refrigerated at 3 °C for 3 months to satisfy stratification requirements. We used 54 nuts each from 13 open-pollinated American chestnut sources, each representing one or more half-sib families from three latitudinal regions in the eastern United States (Table 1). Sources include one each from Vermont and New Hampshire, two each from New York and Maine (northern sources); one from New Jersey and two each from Maryland and Pennsylvania (central sources); one each

Table 1.—Source codes, location information, latitude and longitude for open-pollinated American chestnut seed source (each representing one or more half-sib families) used in the Green Mountain National Forest silvicultural study

Code	County, State	Region	Latitude	Longitude	Elevation (m)
KY1	Metcalfe County, KY	South	37° 00' 16" N	85° 37' 34" W	269
MD1	Montgomery County, MD	Central	38° 57' 53" N	77° 5' 33" W	100
NC1	Jackson County, NC	South	35° 22' 21" N	82° 47' 29" W	1,387
NJ1	Monmouth County, NJ	Central	40° 36' 20" N	73° 07' 10" W	20
NY1	Westchester County, NY	North	41° 19' 41" N	73° 41' 10" W	94
PA1	Franklin County, PA	Central	39° 59' 38" N	77° 23' 55" W	600
PA2	Mercer County, PA	Central	41° 20' 58" N	80° 04' 58" W	384
VA1	Smyth County, VA	South	36° 49' 40" N	81° 25' 49" W	1,036
NY2	Wyoming County, NY	North	42° 37' 44" N	78° 03' 17" W	417
ME2	Knox County, ME	North	44° 10' 55" N	69° 08' 09" W	68
VT1	Chittenden County, VT	North	44° 31' 39" N	73° 12' 11" W	57
ME1	Piscataquis County, ME	North	145° 09' 35" N	69° 04' 58" W	101
VA2	Smyth County, VA	South	30° 51' 55" N	81° 26' 10" W	1,041

from North Carolina, Tennessee, and Virginia, and two from Kentucky (southern sources). Nuts were germinated and seedlings grown in the greenhouse located at the U.S. Forest Service in South Burlington, VT. Nuts were planted in small cone-shaped pots in a potting mix containing 1:1:1 peat/perlite/vermiculite (Gurney 2010). Seedlings were provided with supplemental lighting, water, and fertilizer (a one-time dose of Miracid© Plant Food 30-10-10; Scotts Miracle-Gro Products, Inc., Marysville, OH) to maximize greenhouse growth, and were outplanted into field plots on the GMNF in June 2009. The spacing of seedlings was approximately 2.5 by 2.5 m with variations based on topography and ground cover. Seedlings also received the following cultural treatments when planted: (1) 0.9 by 0.9 m black competition mats to reduce competition from other vegetation, (2) 7.5-cm-diameter, 25-cm-tall cylindrical aluminum shelters buried approximately 10.0 cm into the soil to protect seedlings from rodent damage, and (3) 1.2-m-high, 0.75-m-diameter welded-wire guards to protect seedlings from deer browse. No differences in snow accumulation or melt associated with seedling protection were noted.

METHODS

We measured the height (cm) from base to uppermost branch tip and diameter (mm) at the base of each seedling at the time of planting in June 2009 and again following a single growing season in October 2009. We calculated changes in height and diameter (October - June measurements) to evaluate the influence of region and source within region on growth.

Visual assessments of winter shoot injury were made in July 2010. Injury was quantified as the sum of the lengths (cm) of damaged (dark colored and sunken) stem on each terminal shoot (leader and branches) with no new growth.

Analyses of variance (ANOVA) were used to test for the significance of differences in seedling height and diameter growth, and winter shoot injury among the regions of nut origin and sources within region using JMP statistical software (SAS Institute, Inc., Cary, NC). Tukey HSD tests were used to test for differences among sources within each region. Homogeneity of variance was tested for each measurement parameter using the O'Brien's, Brown-Forsythe, Levene's and Bartlett's tests within JMP. Data were adjusted when needed using the Box-Cox transformation (Montgomery 2001) to satisfy the assumption of homogeneity of variances. For all tests, differences were considered statistically significant when $P \leq 0.05$. The linear associations of winter shoot injury with growth and nut cold tolerance (assessed separately; Saielli 2011) were quantified using regression analyses.

RESULTS

No differences in height or diameter growth attributable to the region of nut origin were evident (Fig.1). However, significant differences among the sources within the region were detected for height growth (in the northern region) and diameter growth (in the southern and central regions) (Fig. 1 and Table 2). Variability in height growth was quite large in the northern region, which included sources with some of the greatest (NY1) and least (ME1 and ME2) growth.

As was seen for growth, no differences in winter shoot injury attributable to region were found (Fig. 1). But like diameter growth, significant differences in winter injury among sources were found within two regions, the southern and northern regions (Fig. 1).

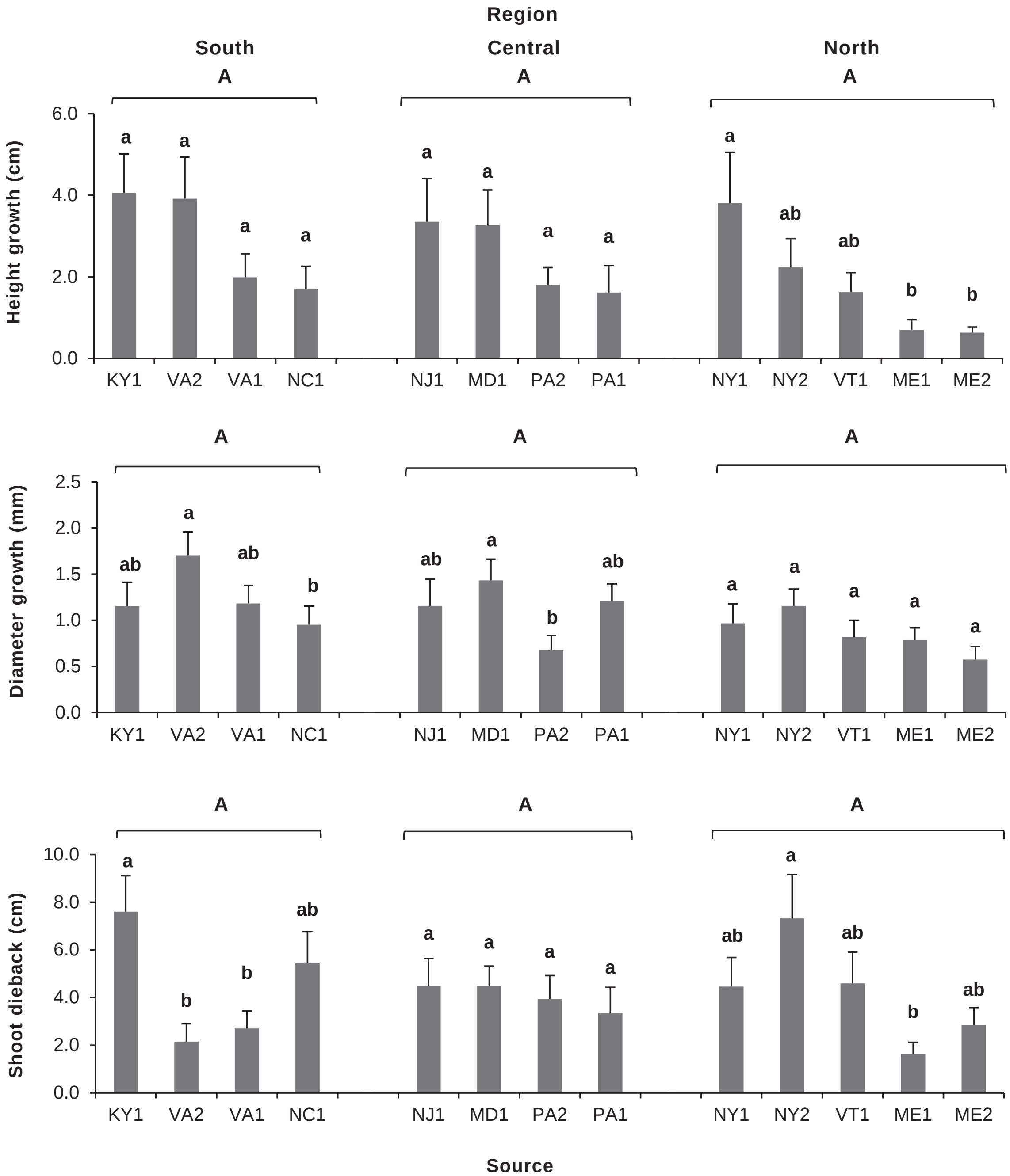

Figure 1.—Mean (± SE) height and diameter growth, and shoot dieback for American chestnut seedlings grown on the Green Mountain National Forest. Regional means with the same upper case letters are not significantly different. Source means within each region with different lower case letters are significantly different based on Tukey HSD tests ($P < 0.05$).

Table 2.—ANOVA tables showing the sources of variation (SOV), degrees of freedom (DF), sums of squares(SS), mean square (MS), and F and P values for the statistical tests used to evaluate differences in (A) height growth, (B) diameter growth, and (C) winter shoot dieback

(A) Height growth

SOV	DF	SS	MS	F	*P*
Region	2	144.19	72.10	1.053	0.384
Source [Region]	10	685.87	68.59	2.448	0.007
Error	640	17932.23	28.02		
Total	652	18767.29			

(B) Diameter growth

SOV	DF	SS	MS	F	*P*
Region	2	17.68	8.84	2.156	0.166
Source [Region]	10	41.07	4.11	1.960	0.035
Error	640	1341.05	2.10		
Total	652	1399.80			

(C) Winter shoot dieback

SOV	DF	SS	MS	F	*P*
Region	2	22.46	11.23	0.058	0.944
Source [Region]	10	1958.03	195.80	3.074	0.001
Error	640	40765.15	63.70		
Total	652	42745.64			

DISCUSSION

Considerable variation in growth and winter shoot injury was found among the 13 American chestnut seed sources evaluated. There was an approximate fourfold range in mean height growth, a threefold range in diameter growth, and a fourfold range in winter shoot injury among seed source means (Fig. 1). Although variation attributable to source was noteworthy, no broad influence of region of origin was evident. The apparent lack of regional influences on seedling growth and winter injury is similar to an earlier assessment of American chestnut nut cold tolerance that found significant source-to-source differences but no evidence of regional adaptation among the seven seed sources assayed (Schaberg et al. 2009). A lack of regional adaptation could be the result of massive tree and associated germplasm loss following blight introduction, so that the few reproductive American chestnut evaluated here better represented other genetic influences (e.g., founder effects, genetic drift, or inbreeding depression following steep population declines) rather than genetic adaptation to regional climate. However, various environmental factors (most notably elevation and proximity to large bodies of water) combine with latitudinal influences to exacerbate or moderate temperatures across the landscape. Considering this, it is possible that a division of sources into categorical groups more directly tied to temperature regimes at source locations (and that incorporate elevational and other influences) would do a better job of differentiating source adaptations to climate relative to the broad regional patterns evaluated here.

In general, there appeared to be a tradeoff between the average growth and winter injury among sources. Although not strong, a significant linear regression between the mean height growth (cm) and winter shoot injury (cm) ($P = 0.03$, $R^2 = 0.39$, Saielli 2011) indicated that sources with the greatest growth during the growing season also tended to experience the most shoot dieback the following winter. A tradeoff between growth and protection is a common theme in plant ecology, including the adaptation of species to the cold (Howe et al. 2003, Loehle 1998). However, a tradeoff between growth and freezing protection would impose an additional challenge to American chestnut breeding programs: identifying sources that counter overall trends and exhibit reasonable growth but that also have acceptable cold tolerance. The combination of good growth and adequate winter shoot protection is possible (e.g., see source VA2 – Fig. 1). However, identification of atypical sources that combine these traits would further complicate breeding efforts. Unfortunately, testing individual source performance in plantings is costly and time consuming, especially when assessing winter shoot injury, because results rely on stochastic exposures to ambient temperature lows that challenge physiological limits. As an alternative to growing and testing the winter shoot injury of seedlings, laboratory estimates of nut cold tolerance were evaluated for use as an indicator of the winter hardiness of seedling shoots. In a separate study (Saielli 2011), we measured the cold tolerance of nuts from 12 of the same seed sources that we assessed for winter shoot injury. Cold tolerance measurements estimate the temperature at which tissues exhibit freezing injury approximating 50 percent cell mortality, so a more negative temperature associated with injury indicates greater cold tolerance. The linear regression of mean nut cold tolerance and winter shoot injury for these sources was significant, positive, and strong ($P < 0.0025$, $R^2 = 0.67$, Saielli 2011), suggesting that nut cold tolerance measurements (that can be obtained in weeks rather than the years needed for plantation-based assessments of shoot injury) may be a reasonable screening tool for identifying sources with superior hardiness.

The substantial variation in growth and winter shoot injury we measured for the 13 seed sources evaluated suggests that there is meaningful genetic variation among remaining American chestnut populations. This variation highlights the potential for positive selection for these and likely other traits within American chestnut breeding programs. Breeding efforts have long focused on selection for blight resistance because this is by far the single greatest factor limiting the health and productivity of the species. However, as breeding trials progress and blight resistance is achieved, active selection for other traits that impart ecological or economic benefits (such as enhanced growth or shoot survival) should be incorporated into breeding efforts. Indeed, because much of the breeding for blight resistance has relied on germplasm from the heart of the species' range, it may be particularly important to identify sources of local adaptation that could foster species adaptation and survival at the limits of the species' environmental tolerances (such as cold high elevation and northern sites).

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REGIONAL AND GEOMORPHIC INFLUENCE ON THE PRODUCTIVITY, COMPOSITION, AND STRUCTURE OF OAK ECOSYSTEMS IN THE WESTERN CENTRAL HARDWOODS REGION

Amber M. Steele, John M. Kabrick, and Randall J. Miles[1]

Abstract.—The steeply dissected glaciated landscapes of the Chariton River Hills Ecological Subsection (CRHES) in northern Missouri have extensive, but largely unmanaged, oak forests that are relatively unstudied. There is increasing interest in these forests for oak ecosystem restoration, ecological site description, and production of oak timber for biofuels. Our objectives were to determine how productivity, composition, and structure varied across the CRHES and locally by slope position and aspect. We inventoried vegetation and soils at 48 sites on upper and lower slope positions paired by northeast-facing and southwest-facing aspect classes on six minimally disturbed sites across the CRHES. Among sites, the site index of the two most abundant species ranged from 51 to 58 feet (white oak) and 51 to 62 feet (northern red oak) For white oak, site index was significantly greater on north-facing aspects ($P<0.01$) and lower slopes ($P=0.1$). White oak stocking was greater on southwest-facing aspects ($P<0.01$) and on upper slopes ($P=0.2$). White oak, northern red oak, and black oak make up the majority of the overstory; however, ironwood, blackhaw, white ash, and other species make up most of the understory and the large advance reproduction layer. Meeting typical oak ecosystem restoration or oak regeneration objectives will require the application of prescribed fire or other disturbances to reduce the understory density to provide light and growing space for a variety of woodland ground flora and oak seedlings, particularly on lower northeast-facing slopes.

INTRODUCTION

Geomorphic factors such as the land surface shape, slope position, and aspect have long been recognized to influence soil properties as well as forest composition and productivity (Carmean 1975, Fu et al. 2004, Hicks and Frank 1985, Pregitzer et al. 1983), particularly in landscapes having steep slopes and a high degree of topographic relief. The Chariton River Hills Ecological Subsection (CRHES) within the Iowa and Missouri Heavy Till Plain Major Land Resource Area (MLRA) is characterized by its steep slopes and extensive oak forests covering a large portion of northern Missouri (Fig. 1). The CRHES has the greatest topographic relief of interior northern Missouri (up to 250 feet), and is bordered on the east and west by more gently sloping lands predominantly used for agriculture. However, the forests in the CRHES are rarely subjected to manipulative treatments and consequently little is known about their productivity, composition, and structure.

Interest is increasing in the forests of the CRHES from private landowners and public land management agencies for oak forest and woodland restoration and for production of oak timber and biofuels. In addition, the Natural Resources Conservation Service (NRCS) of the U.S. Department of Agriculture has an interest in improving its understanding of the vegetation-site relationships in this MLRA to develop ecological site descriptions (ESDs) and to update the National Cooperative

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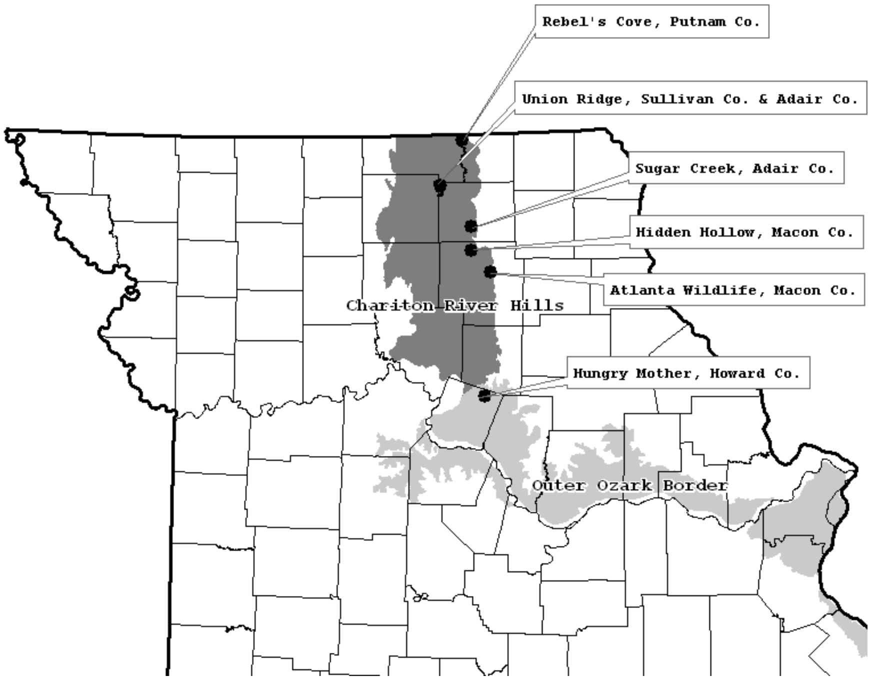

Figure 1.—Chariton River Hills Ecological Subsection (dark gray); Outer Ozark Border (light gray); filled black circles indicate project locations listed from south to north: Hungry Mother Conservation Area (CA), Atlanta Wildlife Area, Hidden Hollow CA, Sugar Creek CA, Union Ridge CA, and Rebel's Cove CA (Nigh and Schroeder 2002).

Soil Survey. Ecological site descriptions are a level of ecological land classification analogous to ecological landtypes (ELTs) used by the U.S. Forest Service. Geomorphic factors are important site-level determinants of site productivity and species composition used in both of these classification systems. Our study objectives were to determine how the productivity, composition, and structure of oak ecosystems vary regionally across the CRHES and locally by slope position and aspect.

STUDY AREA

Six sites (Fig. 1) were selected from central Missouri north to the Missouri-Iowa border. Sites were selected based upon a number of criteria including: (1) locality within or near the CRHES, (2) similarity of soils and topography, (3) accessibility, and (4) absence of recent timber harvesting, burning, or other anthropogenic disturbances. Consequently, all six sites were located on land owned by the Missouri Department of Conservation. All sites, except Hungry Mother Conservation Area, were within the CRHES. The site at Hungry Mother Conservation Area was included because its soils and physiography closely resembled that of the CRHES.

Study soils included the soil series Winnegan and Lindley. These soils were benchmark series due to their ecological significance and large mapping extent. Winnegan and Lindley soils are formed in calcareous Pre-Illinoian (2.5 million to 500,000 years ago) glacial till, and developed under humid climate conditions. Common characteristics of these soils include a well-expressed argillic horizon and soft masses of calcium carbonate commonly found in the lower part of the profile (Soil Survey Staff 2011). Differences between distinguishing characteristics of these soil series are slight. Winnegan soils are classified as very deep, moderately well drained, fine, Oxyaquic Hapludalfs, and Lindley soils are classified as well drained, fine-loamy, Typic Hapludalfs. These soils presently support central hardwood species such as white oak (*Quercus alba* L.), black oak (*Quercus velutina* Lam.), northern red oak (*Quercus rubra* L.), and hickory (*Carya* L. spp.).

Pre-European settlement vegetation of the study area was largely fire-adapted woodlands, with forests on steeper slopes and narrower valleys (Nigh and Schroeder 2002). Schroeder (1982) found that the presence of an intricate pattern of prairie and forests in Missouri was a major factor in the richness of wildlife in presettlement Missouri, and that the CRHES had the most intricate prairie-forest pattern in the state. Conversion of uplands for agricultural production began in the late 1800s (Schroeder 1982). Agricultural and developmental pressures have reduced much of the original forested structure in northern Missouri, and many once forested slopes are now cleared for grazing. The current landscape is mostly pasture with many tracts of second-growth oak-hickory forest on the steepest areas (Nigh and Schroeder 2002), which contain soil map units of either Winnegan or Lindley soil series as the dominant component.

METHODS

To encompass forested portions of the CRHES that were affected by differences in aspect, sampling was done on two slope positions (upper and lower positions of backslopes, (slopes >15%)) and two aspect classes (protected (north to northeast-facing) and exposed (south to southwest-facing)) at two random locations within each of the six sites (conservation areas) for a total of 48 samples. Plots were not placed on neutral aspects (115 to 155° and 295 to 335°).

Nested, concentric vegetation plots were used to inventory woody vegetation for each combination of slope position by aspect class at each location. Trees 1.5 inches diameter at breast height (d.b.h.) or larger were inventoried in a circular 0.12-acre plot and trees less than 1.5 inches d.b.h but larger than 1.5 feet tall were inventoried in a circular 0.012-acre subplot by height classes: 1.50 to 2.99 feet, 3.00to 4.49 feet, and >4.5 feet. Trees up to 1.5 feet tall were inventoried in a 0.006-acre subplot.

Site index data were collected on overstory plots by sampling up to three trees of each of the most abundant tree species present: white oak or northern red oak. Trees selected were (1) dominant or codominant, (2) had no indication of being open grown, and (3) had no indication of suppression (Carmean et al. 1989). For selected trees, height was estimated using a clinometer and the age at d.b.h. was determined from a single core sampled with an increment borer 4.5 feet above ground. Site index was computed using equations formulated for forest tree species in the eastern United States (Carmean et al. 1989) and parameters from oak species in Missouri (McQuilkin 1974, 1978). Trees per acre and basal area per acre were calculated and used to determine percent stocking (Gingrich 1964, 1967).

To quantify site variables, a soil pit was excavated within each overstory plot to a depth of 80 inches; genetic horizons were morphologically delineated and described according to the NRCS Soil Survey Field Book for Describing and Sampling Soils (Schoeneberger et al. 2002). Soil samples were collected from each horizon for full soil characterization analysis by the University of Missouri Soil Characterization Laboratory and select data are presented in Table 1. Percent slope, aspect, and slope morphometry were also recorded at each plot.

To examine the effects of aspect and slope position, data were analyzed using the MIXED procedure (SAS Institute Inc., 2002-2008). We used a hierarchical linear mixed model with aspect and slope position as nested, crossed, fixed effects and location, and location within site as random effects. This model tested the effect of aspect or slope position using the aspect*slope position*site interaction

Table 1.—Summary of average values for select site variables by diagnostic horizon for the epipedon (0 inches to the top of the argillic horizon) and upper and lower subsurface horizons (divided at the midpoint from the top of the argillic horizon to the bottom depth of 80 inches) (Standard deviation is given below each average)

Diagnostic horizon	Texture	Clay %	Sand %	AWC[a] in.	CEC[b,c]	Ca[b]	Mg[b]	K[b]	Bs[c,d] %	pH (H_2O)
Epipedon	Loam	14 ±4.2	41 ±12	1.1 ±0.50	14 ±3.9	6.3 ±3.8	1.2 ±0.53	0.25 ±0.09	51 ±19	5.2 ±0.52
Upper subsurface	Clay loam	36 ±5.1	33 ±8.6	4.2 ±0.85	23 ±4.1	12 ±7.7	2.7 ±1.2	0.27 ±0.07	58 ±16	5.2 ±0.65
Lower subsurface	Clay loam	28 ±4.9	37 ±9.2	6.9 ±0.75	16 ±2.7	33 ±13	3.7 ±2.0	0.18 ±0.08	94 ±11	7.3 ±0.91

[a] Estimated available water capacity.
[b] Units are in $cmol_c/kg$.
[c] Extracted by ammonium acetate.
[d] Base saturation.

at the 0.05 significance level. We also examined regional differences in site index using the REG procedure (SAS Institute Inc. 2008) by including the variables: percent clay, percent silt, available water capacity, cation exchange capacity, and percent base cation saturation averaged by location.

RESULTS

Site Productivity

Across the CRHES, site index ranged from 51 to 58 feet (white oak) and 51 to 62 feet (northern red oak) (Fig. 2). Site index was slightly lower on the southernmost and northern most locations but regression analyses between site index and site variables (percent clay, percent silt, available water capacity, cation exchange capacity, and percent base cation saturation) did not show significant relationships, suggesting some other cause for regional differences. We observed that sites with lower site index values had older, slower growing trees (particularly the white oaks) including Hungry Mother (average age 128 years), Atlanta Wildlife (average age 88 years), and Union Ridge (average

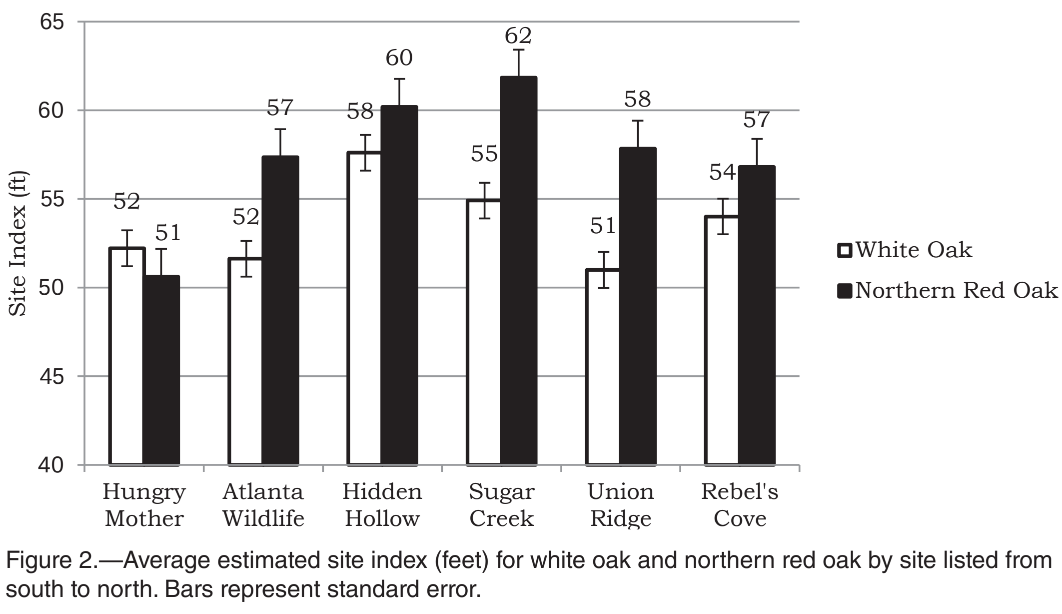

Figure 2.—Average estimated site index (feet) for white oak and northern red oak by site listed from south to north. Bars represent standard error.

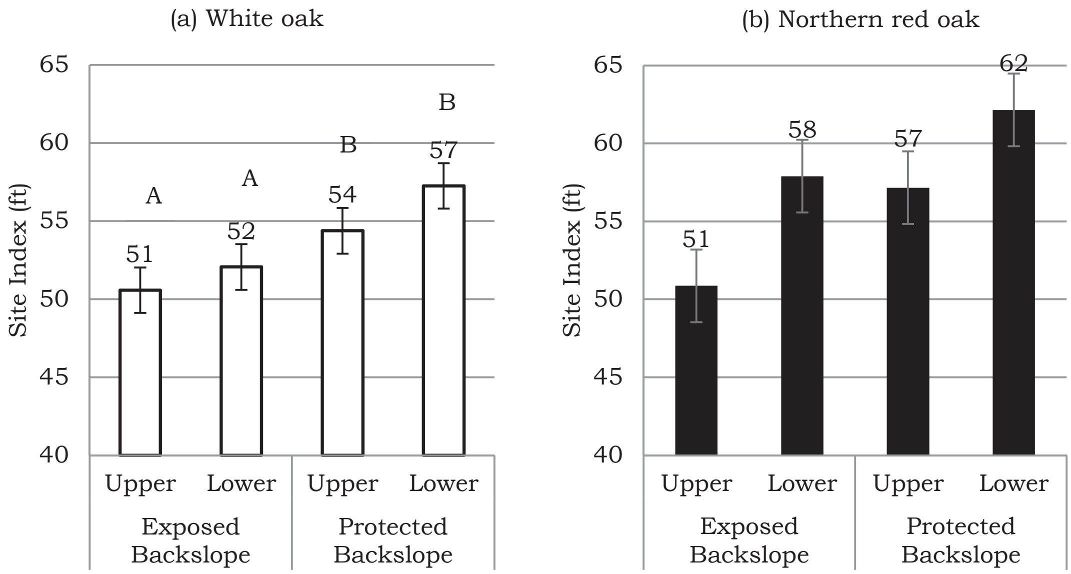

Figure 3.—Estimated site index for (a) white oak and (b) northern red oak by geomorphic component. Site index is significantly greater (P<0.01) for white oak on protected topographic aspects and nominally greater (P=0.1) on lower hillslope positions. Letters represent unique populations by topographic aspect (P<0.05). Bars represent standard error.

age 85 years), suggesting that site index may have been underestimated because ages were beyond the range at which site index curves were developed. Despite the lack of regional trends, there was a distinct geomorphic effect on the site index. Site index values for white oak were significantly greater on protected aspects (P<0.01) and nominally greater (P=0.1) on lower slope positions (Fig. 3). For northern red oak, site productivity appeared greater on lower slope positions and protected aspects, but due to an imbalance in the dataset the model was not run (Fig. 3). This imbalance was most likely a result of red oak species (northern red oak and black oak) not occurring on every plot. However, because northern red oak and black oak site index values were nearly equivalent (Johnson et al. 2009), the values of these species were averaged and results were significantly (P<0.01) greater on lower slope positions. Results indicated that slope position and aspect had a greater influence on site productivity than regional factors and that the greatest productivity was on lower slope positions of protected aspects.

Composition and Structure

All stands were in the understory re-initiation stage of stand development (Johnson et al. 2009, Oliver and Larson 1996) and were fully or overstocked (Gingrich 1967). Stocking ranged from 78 to 112 percent (Table 2). On a stocking basis, white oaks (dominantly white oak) were the most abundant overstory species at every site, followed by red oak species (mainly northern red oak and some black oak), ironwood (*Ostrya virginiana* (Mill.) K. Koch), hickories, and white ash (*Fraxinus americana* L.). Much as with productivity, we found that aspect and slope position had a significant effect of the stocking of white oak and red oak species (Fig. 4). White oak stocking was significantly greater on exposed slope aspects (P<0.01) and nominally greater on upper slope positions (P=0.1). Red oak stocking was nominally greater on protected aspects and lower slope positions.

Table 2.—Average percent stocking for overstory species (>1.5 in. d.b.h.) listed by location from south to north

Species group	Hungry Mother	Atlanta Wildlife	Hidden Hollow	Sugar Creek	Union Ridge	Rebel's Cove	Average stocking
White oak spp.	53	83	47	60	51	88	63
Red oak spp.	12	20	25	16	21	8	18
Ironwood	9	1	<1	4	7	4	4
Hickory spp.	7	5	3	3	2	2	4
White ash	<1	4	<1	<1	9	<1	3
Other Spp.[a]	1	<1	1	<1	0.0	<1	<1
Elm[b]	2	<1	<1	<1	<1	1	1
Sugar maple[c]	3	0.0	0.0	0.0	0.0	0.0	<1
Black cherry[d]	<1	<1	<1	<1	1	<1	<1
Black walnut[e]	1	0.0	0.0	0.0	0.0	<1	<1
Serviceberry[f]	<1	0.0	<1	0.0	<1	<1	<1
Ohio buckeye[g]	<1	0.0	0.0	0.0	<1	<1	<1
Total Stocking	89	112	78	84	92	105	94

[a] Mainly composed of red mulberry (*Morus rubra* L.), eastern redbud (*Cercis canadensis* L.), and hackberry (*Celtis occidentalis* L.).
[b] *Ulmus spp.* L.
[c] *Acer saccarrinum* L.
[d] *Prunus serotina* Ehrh.
[e] *Juglans nigra* L.
[f] *Amelanchier arborea* Michx. f.
[g] *Aesculus glabra* Willd.

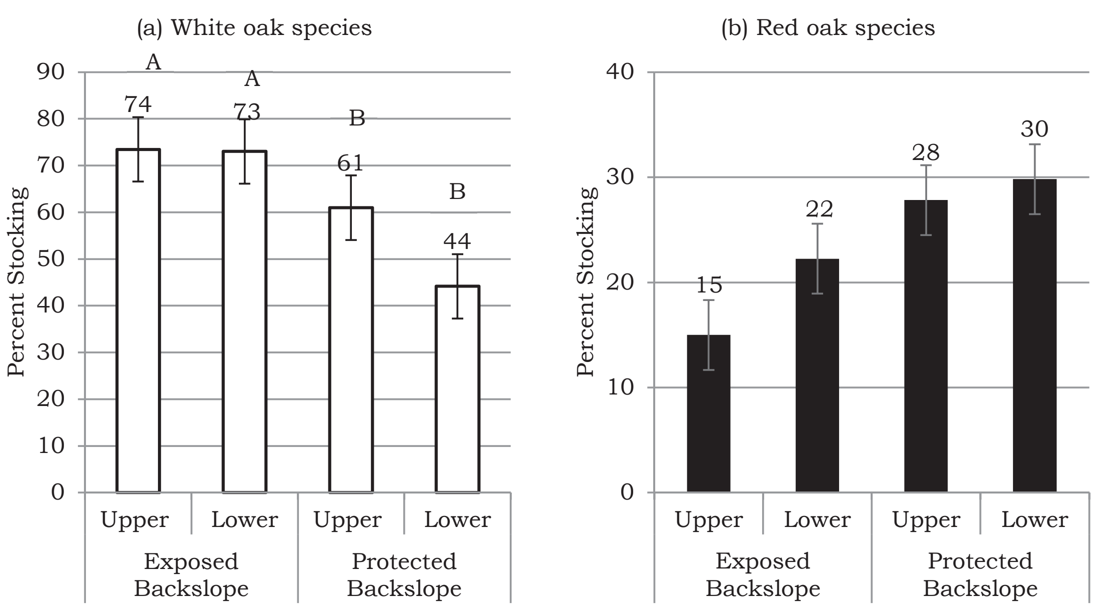

Figure 4.—Average percent stocking for (a) white oak species and (b) red oak species groups by geomorphic component. Stocking was significantly higher for white oak species on exposed topographic aspects (P<0.01) and nominally higher for upper hillslope positions (P=0.2), and red oak species stocking was nominally greater on lower northeast-facing slopes. Letters represent unique populations by topographic aspect (P<0.05). Bars represent standard error.

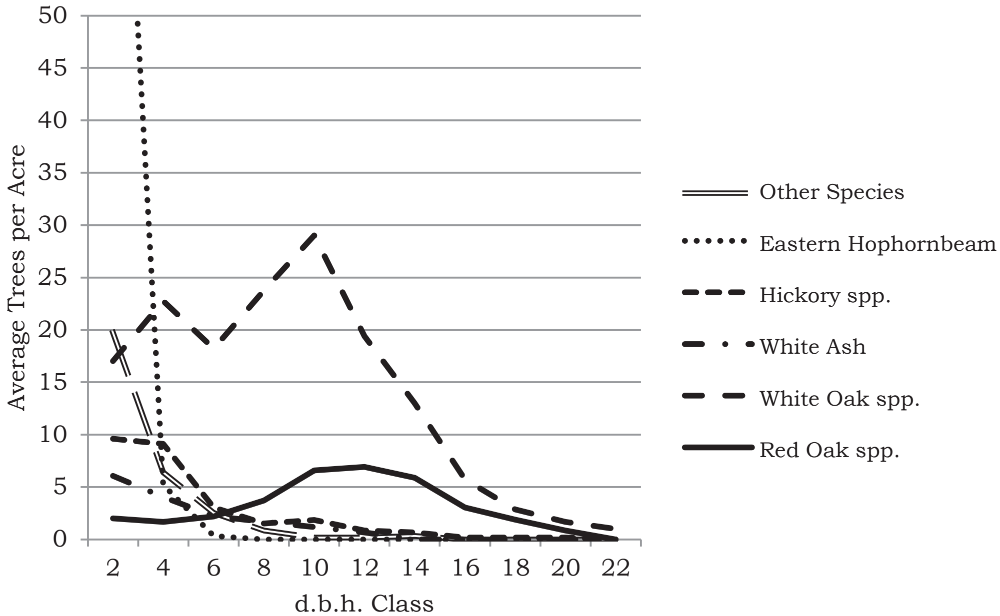

Figure 5.—Average trees per acre by diameter class for eastern hophornbeam, hickory species, white ash, white oak species, red oak species, and the "other species" category. The y-axis has been adjusted to illustrate species less abundant than eastern hophornbeam, which is most abundant in the 2- to 4-inch diameter class with a total of 92 trees per acre.

The diameter distribution (Fig. 5) indicated that oaks exhibited a more normal or bell-shaped distribution; white oak species were greatest in the 8- to 10-inch diameter class and red oak species were greatest in the 10- to 14-inch diameter class. Other species demonstrated a reverse-J distribution, including ironwood, the category "other species" (mainly elm, black cherry, and serviceberry), hickory, and white ash. Ironwood was the most abundant species in the 2- to 4-inch diameter class, reaching an average of 92 trees per acre in this class. In the overstory, ironwood stocking was significantly (P=0.03) greater on lower slope positions, regardless of aspect.

The large advance reproduction class (species >1.5 feet tall and <1.5 inches d.b.h.) was mostly made up of the category "other species" consisting mainly of blackhaw (*Viburnum prunifolium* L.), redbud, serviceberry, and elm species followed by white ash and ironwood (Table 3). White oak advance reproduction was highly variable from site to site; on sites with below average amounts of white oak, ironwood or the category "other species" make up most of the advance reproduction class with smaller amounts of white ash.

For the large advance reproduction, variation by location lacked clear trends; however, there were some differences by aspect and slope position for this class (Fig. 6). For example, white oak reproduction was greatest on exposed aspects and upper slope positions, the category "other species" was more abundant on lower slope positions, and white ash was greater on upper slope positions.

Table 3.—Average trees per acre (TPA) for the large advance reproduction class[a] for locations listed in order from south to north

Species group	Hungry Mother	Atlanta Wildlife	Hidden Hollow	Sugar Creek	Union Ridge	Rebel's Cove	Avg. TPA
Other spp.	3,087	759	982	1,943	395	1,579	1,457
White ash	405	1,427	1,984	1,164	516	962	1,076
Ironwood	881	587	374	1,134	1,579	911	911
White oak spp.	10	891	1,306	1,619	81	324	705
Blackhaw	506	972	263	121	182	71	353
Hickory spp.	0	91	617	0	20	51	130
Red oak spp.	40	20	46	30	30	10	29
Elm spp.	0	0	132	0	0	0	22
Total TPA	4,929	4,747	5,704	6,011	2,803	3,908	4,683

[a] Species >1.5 feet in height and <1.5 inches d.b.h.

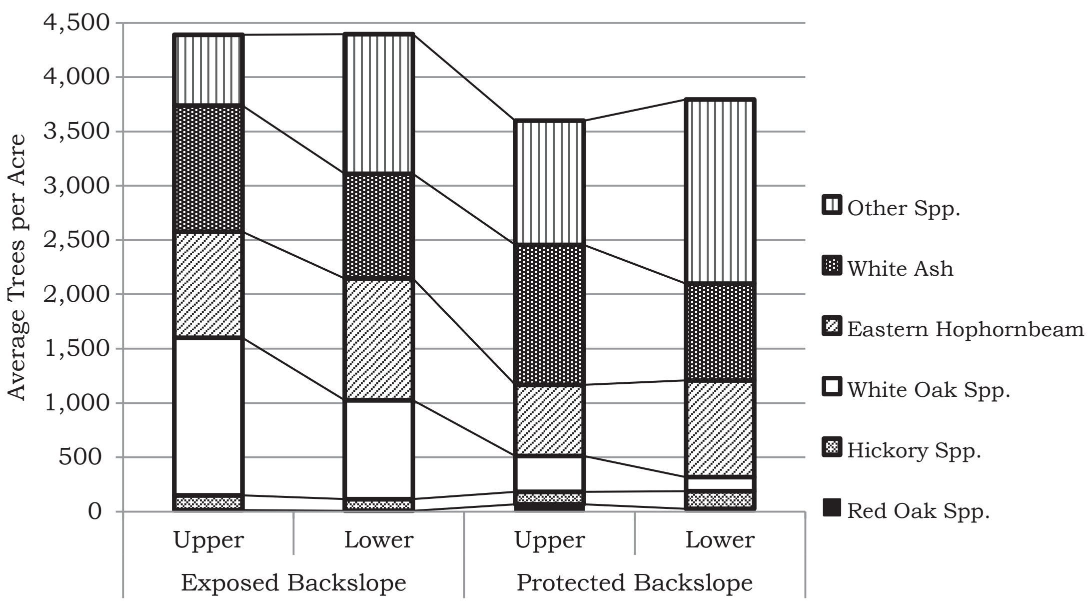

Figure 6.—Average trees per acre by geomorphic component for the large advance reproduction class (species greater than 1.5 feet in height and less than 1.5 inches d.b.h.).

DISCUSSION

The oak forests of the CRHES exhibit low to moderate productivity as indicated by site index values ranging from 51 to 62 feet across the region. These values are lower than oak site indices reported elsewhere in the Central Hardwoods Region. For example, oak site index in West Virginia ranges from 65 to 83 feet (Yawney 1964), and in southern Indiana ranges from 47 to 77 feet on slopes (Jose and Gillespie 1997). Even in the nutrient-poor and droughty soils of the Missouri Ozarks, site index values for oaks equals (54 to 66 feet (Hartung and Lloyd 1969) or exceeds (60 to 70 feet (Kabrick et al. 2004) those observed in the CRHES. This finding was surprising considering the relatively high nutrient and water supply capacity of the glacially derived soils of the CRHES (Table 1) compared to the highly weathered and droughty soils of the Ozark Highlands (Kabrick et al. 2008). This suggests that the low to moderate site productivity of our study region is likely due to factors other than to soil properties such as seasonal rainfall patterns or other factors related to climate. Undoubtedly, genetic degradation due to past management (i.e., potential high-grading) would affect site index values; however, detailed historical information was unknown. Between 2001 and 2005, average annual rainfall in the study area averaged 4 inches less than rainfall in the Missouri Ozarks (National Agricultural Statistics Service 2011). Moreover, regression analyses indicated that regional site index patterns were not related to differences in soil properties or other site factors.

Our analysis demonstrated that locally, geomorphic factors play an important role in governing site productivity because we found the range of average site index on different slope positions and aspects was as great as the average range among all sites across the CRHES. Correlations between aspect and slope gradient with site quality have been well documented (Brown 2007, Hannah 1968, Hartung and Lloyd 1969) and in general north- to east-facing slope aspects exhibit greater productivity than south- to west-facing slope aspects in the Northern Hemisphere (Johnson et al. 2009). Our results were consistent with these trends and indicated that the most productive sites in the CRHES are found on lower slope positions of protected aspects.

Topographic differences in site productivity in the CRHES were reflected in species composition. We found red oak stocking was greater on lower, north-facing slopes and white oak stocking was greater on upper, south-facing slopes. Northern red oak is reportedly more abundant in coves or lower north-facing slopes where water supply is generally greater than on other slopes (Johnson et al. 2009, Sander 1990) and white oak is reportedly much more broad in its distribution with respect to site factors (Rogers 1990). Oaks in the CRHES also exhibited classic bell-shaped diameter distributions as they typically do in mesic natural mixed-oak stands in the Central Hardwoods Region (Roach and Gingrich 1968, Schnur 1937). Commonly, more shade-tolerant species occupy smaller diameter size classes making up the tail of the reverse-J-shaped diameter distribution that is observed when all species are included (Johnson et al. 2009). This finding was in contrast to drier oak ecosystems such as those of northern Lower Michigan (Johnson 1992) or the Ozark Highlands (Loewenstein et al. 2000) where site conditions such as low nutrient status and water holding capacity (Kabrick et al. 2004) limit the number of shade-tolerant species in the understory allowing moderately tolerant white oaks to accumulate in the understory and develop a reverse-J distribution.

Despite their abundance in the present-day overstory, oaks may not be abundant in the future forests of the CRHES. Successful oak regeneration requires the accumulation of advance reproduction before recruitment following a canopy-removing disturbance (Johnson et al. 2009). In comparison to upper slope positions of exposed aspects, large advanced reproduction of white oak was less abundant on all other positions with the smallest amounts on lower slope positions of north-facing aspects. Before European settlement, fire was an important disturbance factor in the CRHES (Schroeder 1982). With about 50 percent of the area in prairie and an intricate pattern of prairie and forest (Schroeder 1982), it is likely that fire periodically spread to forested slopes of the CRHES. This fire likely favored the accumulation of oak seedlings by reducing the density of fire-sensitive oak competitors, positioning oaks to recruit into the overstory following larger, canopy-removing disturbances. Fire suppression, especially, since the early 20th century (Nowacki and Abrams 2008), has allowed shade-tolerant, fire-sensitive species to accumulate. Returning fire to these forests would likely reduce the density of fire-sensitive species and increase the density of oak advance reproduction and some of the forbs, legumes, sedges, and grasses characteristic of fire-dependent woodland ecosystems (Taft 2009).

In the absence of fire, it is unclear what species would eventually recruit into the forest overstory in this region following a canopy-removing disturbance. For example, of the two most abundant species in the advance reproduction layer, ironwood is not an overstory species and as such would not be a long-term competitor. Likewise, white ash is seldom abundant in the overstory of Central Hardwoods forests (Kabrick et al. 2004, Schlesinger 1990, Yaussy et al. 2003). In addition, white ash has an indeterminate future throughout North America because of the increasing spread of emerald ash borer (*Agrilus planipennis* Fairmaire), which may eventually extirpate ash species in the Central Hardwoods Region. Due to low quantities of oaks in the large advance reproduction and the limitations of oak regeneration from stump sprouting (Johnson et al. 2009), decreased oak stocking from current levels would be likely.

CONCLUSIONS

This study demonstrated that the geomorphic factors of aspect and slope position are important determinants of productivity, composition, and structure in the dissected glacial till plain forests of the CRHES. The role played by local geomorphic factors in vegetation-site relationships will remain an important consideration for refinements to the National Cooperative Soil Survey and other land classification systems, especially during the development of landform-scale management tools such as ESDs and ELTs. These geomorphic differences are also important considerations for cost-effective land management decisions. For example, in the CRHES, management efforts (e.g., thinning, prescribed fire) may be most needed on protected aspects and lower slope positions to promote oak accumulation in the understory. Additionally, results from this study have provided baseline data for understanding the present-day productivity, composition, and regeneration potential for land managers and landowners seeking critical information about forests in an otherwise under studied region of Missouri.

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INFLUENCE OF DISTURBANCE ON STAND DEVELOPMENT DURING FOREST SUCCESSION

Jeffrey S. Ward[1]

Abstract.—Eighty years of data on stand development on 39 strip transects were used to elucidate the influence of disturbance on forest composition. Transects were measured at 10-year intervals between 1927 and 2007, except for 1947, and the resulting data include records of 35,953 stems. Disturbances included a wildfire in 1932, single-year defoliations (1964, 1972, 1981), and multi-year defoliations (1961-1963, 1971-1972, 1981). Wildfire reduced basal area by 46 percent. During the first defoliation period, oak basal area mortality averaged 36 (multi-year) and 12 percent (single-year). In 2007, oak density (stems per acre) on burned transects in 2007 was twice that observed on unburned transects, 90 and 42; while maple density was higher on transects that had had only single-year defoliations (190) compared with multi-year defoliation (119). In contrast, birch density was lower on transects with single-year defoliations (97) compared to multi-year defoliation (198). Oak ingrowth was highest following wildfire, 244 stems per acre per decade (SA^{10}) and was negligible during subsequent decades, 6 SA^{10}. Transects with multi-year defoliations averaged 80 birch SA^{10} compared with 44 maple SA^{10} between 1967 and 1997. During that same period, maple ingrowth averaged 35 SA^{10} and birch ingrowth averaged 14 SA^{10} following single-year defoliations. Disturbance type has a long-term impact on forest composition.

INTRODUCTION

Disturbances to different canopy strata can have both short-term (<20 years) and long- term (>20 years) effects on stand composition and structure. Most research has focused on short-term responses to disturbances, including forest management; few published studies span more than a decade on the hardwood forest dynamics. Studying the trajectory of species composition and stand structure for longer than a decade is important because predictions based on short-term observations may, or may not, be accurate (Brose 2010).

Although there is a paucity of information on the long-term effects (> 20 years) of fire in eastern hardwoods, short-term effects have been well documented (Brose et al. 2006). Eleven years after prescribed burning, oak dominance increased with fire intensity in Virginia (Brose 2010). In Rhode Island, 5 to 51 years after high-intensity fires, relative density of oak was twice as high on burned compared to unburned sites (Brown 1960). High-intensity fires did not change the average frequency of black oak (*Quercus velutina*), but did reduce the average frequency of red maple (*Acer rubrum*) and white oak (*Quercus alba*) in New York (Swan 1970).

The short-term impacts of gypsy moth (*Lymantria dispa*r L.) defoliation have been thoroughly studied. Oak diameter growth decreases by 30 to 60 percent during outbreaks (Baker 1941, Brown et al. 1979, Campbell and Garlo 1982, Muzika and Liebhold 1999), and mortality is concentrated in the lower canopy oaks (Brown et al. 1979, Campbell and Sloan 1977, Kegg 1971). In general, these studies reported that diameter growth and tree health recovered 2 to 10 years after heavy defoliation.

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Surprisingly, reports on the effects of gypsy moth defoliations on regeneration are limited to the several years after the defoliation. Studies 4 to 7 years after defoliation found increases of red maple and birch in Pennsylvania and Maryland (Allen and Bowersox 1989, Fajvan and Wood 1996, Hix et al. 1991). Two years after defoliation, red maple and black cherry were the predominant seedling species in West Virginia (Muzika and Twery 1995).

The objective of this research was to compare the effects of three distinct disturbance regimes (wildfire, repeated multi-year defoliations, and single-year defoliations) on forest composition and regeneration over an 80-year period. This information will be useful for forest managers wanting to predict the long-term composition of forests impacted by a variety of disturbance regimes, especially in unmanaged natural preserves.

STUDY AREAS

The first Old-Series study area was established on the Turkey Hill Tract (80 acres), Cockaponset State Forest, Haddam, CT, in 1926. In 1927 three additional Old-Series study areas were established in Meshomasic State Forest, Portland, CT: Cabin (40 acres), Cox (50 acres), and Reeves Tracts (40 acres). These four tracts form a study unique because of its length (80 years), depth (43,560 stems distributed to more than 50 species), breadth of information (species, diameter, crown class, spatial location, etc.), continuity (eight inventories), and replication on four sites.

The history of these study areas was typical of most second-growth forests in southern New England. They are a mixture of abandoned agricultural lands, grazed woodlots, and areas repeatedly cut for fuelwood, charcoal, and lumber (Stephens and Waggoner 1980). The median age of upper canopy oaks was 80 years in 1983, indicating that anthropogenic disturbance ended around 1900. Although there are many American chestnut (*Castanea dentata)* sprouts on all study areas, no large chestnuts were found when the tracts were first inventoried in 1926-27 (Hicock et al. 1931). Upland oaks have dominated both dominant and codominant crown classes since the study began in 1926.

The acidic soils (pH 4.5-6.0) are very stony to extremely stony, fine sandy loams derived from gneiss and schist glacial tills. Mean oak site index was 67 feet (reference age 50 years) on moderately well drained soil. Topography is gently rolling with elevations ranging from 90 to 170 m.s.l. Climatic data are from Hartford, CT, approximately 16 km northwest of the Meshomasic tracts (National Oceanic and Atmospheric Administration 1991). The area is in the northern temperate climate zone. There is an average of 176 frost free days per year. Mean monthly temperature ranges from 25 °F in January to 73°F in July. Average annual precipitation is 44 inches per year evenly divided over all months.

The four Old-Series tracts have had three distinct disturbance regimes since the first inventories. <u>MULTI</u>-Three tracts in Portland had multi-year episodes of moderate to severe defoliation (>35 percent) in 1961-63 and 1971-1972, and a single year of defoliation in 1981 due to gypsy moth, canker worm (*Paleacrita vernata*), and elm spanworm (*Ennomos subsignarius*). These defoliations and subsequent infestations by secondary agents, such as the two-lined chestnut borer (*Agrilus bilineatus*) and shoestring root rot (*Armillaria mellea*), resulted in the loss of more than 90 percent oaks in the intermediate and suppressed crown classes along with half of codominant red oaks (Ward 2007). <u>SINGLE</u> - Moderate to severe defoliations at the Turkey Hill tract were limited to single year episodes in 1964, 1972, and 1981. FIRE - A summer wildfire burned approximately 40 percent of the Turkey Hill tract in 1932. The burned area was inventoried in 1934 to note which trees survived the fire. The wildfire provided abundant growing space for new trees by killing 92 percent of saplings, 58 percent of poles, and 24 percent of sawtimber (Ward and Stephens 1989).

METHODS

Field Measurements

Trees were measured in transect segments 16.5 feet wide and 66 feet long. Transect lines had from 10 to 20 segments and were spaced 264 feet apart on all tracts except Turkey Hill where transects were spaced 330 feet apart. Transect sections adjacent to roads, trails, and other human disturbance were excluded from this analysis, as were sections in poorly drained muck soils. Trees were mapped to the nearest 4 inches. These maps were used to relocate trees in the subsequent inventories of 1937, 1957, 1967, 1977, 1987, 1997, and 2007. The species, diameter, and crown class of each tree were also recorded. Minimum diameter (at 4.5 feet aboveground) was 0.6 inch in 1927 and 1937; since 1957, the minimum diameter has been 1.5 inches. A total of 35,953 individual tree records were used in this analysis. More details on study protocols can be found in Ward et al. (1999).

A special concern of long-term studies is maintenance of data quality, i.e., consistency of data measurements and methods. Transects locations were permanently established with rock cairns and wooden stakes at 132-foot intervals in 1926. The wooden stakes were replaced by metal bars in 1976. The centerline of each transect segment was located by stretching a tape between stakes. Individual trees were then identified by matching their location, species, and diameter with previous records using detailed maps from the previous inventory.

Data Analysis

To allow estimation of stand-level changes of density and basal area, individual transects of each tract were considered as a sample unit. Because transects were at least 264 feet apart within a tract, at least three tree heights apart, pseudo-replication was not considered a factor. Thirty-nine transects that were at least 200 feet long and without anthropogenic disturbance, primarily cutting, were included in the study: MULTI (n=26), SINGLE (n=7), FIRE (n=6). Density and basal area estimates for each transect were transformed to per acre values before analysis because lengths varied by both the number of initial segments per transect and the number of segments that were excluded because of anthropogenic disturbance.

To simplify analysis of changes over the past 80 years, this report examined three species groups in detail: maple (*Acer saccharum*, *A. rubrum*), oak (*Quercus rubra*, *Q. velutina*, *Q. coccinea*, *Q. alba*, *Q. prinus*), birch (*Betula alleghaniensis*, *B. lenta*). These nine species accounted for 74 percent of observed stems of species that had the potential of forming part of the upper canopy in a mature forest. Ingrowth was defined at those trees that grew large enough between surveys to be measured for the first time, i.e., new trees.

For combined species, repeated measures ANOVA for density and basal area using SYSTAT 13 was used with survey year as the within subjects factor and disturbance type as the between subjects factor. Differences were judged significant at $p < 0.05$ using the conservative Greenhouse-Geisser

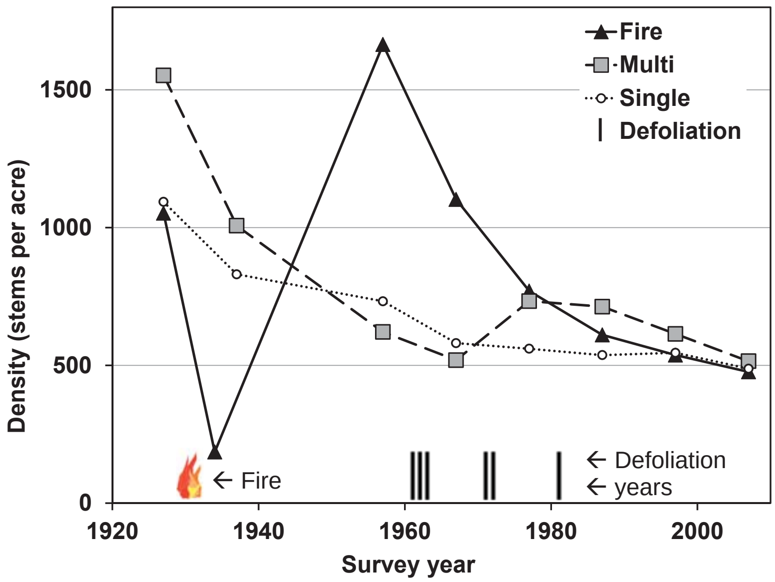

Figure 1.—Stand density (stems/acre) by disturbance type and survey year for Old-Series tracts in central Connecticut. Disturbance types: FIRE-wildfire in 1932, MULTI-repeated multi-year defoliations, and SINGLE-single-year defoliations.

correction for deviation from compound symmetry. For each species group and for combined species, a one-factor (disturbance type) ANOVA weighted by transect length was used to compare the influence of disturbance type on density and basal area in 2007. Tukey's HSD test was used to test for significant differences $P < 0.05$.

RESULTS

Density

Repeated measures ANOVA indicated stand density was not independent of the interaction of survey year and disturbance type ($F=15.05$, $df=14$, $P<0.001$). Stand density (stems/acre) steadily declined since 1927 on transects that experienced single-year defoliation episodes (Fig. 1). Transects burned by the 1932 wildfire had a sharp drop and then rapid increase of stem density through 1957, followed by a steady decline through 2007. A third pattern was observed on transects that had multi-year defoliations; density declined through 1967 and then increased for 20 years before beginning to decline again. Remarkably, by 1997, density did not differ among transects that had experienced the distinct disturbance regimes ($F=1.463$, $df=2$, $P=0.245$) and was nearly identical in 2007, 476 to 515 stems/acre.

The decline on transects with single-year defoliations was not uniformly distributed among species groups; oak declined by 82 percent and birch by 60 percent, while maple actually increased by 27 percent (Table 1). The more rapid decline of oak relative to other species is not unique to this study and has been observed in other unmanaged forests from North Carolina (Christensen 1977), north to Massachusetts (Foster et al. 1998), and west to Missouri (Nigh et al. 1985).

Recent research has highlighted the importance of understory disturbance, e.g., prescribed burning, if oak is to be maintained as a component of the eastern deciduous forest (Brose et al. 2006). Oak density dramatically increased in the decades following the 1932 wildfire and was more abundant than on the unburned transects 65 years after the burn ($F=4.886$, $df=2$, $P=0.013$). Shorter term (20- to 30-year) increases of maple and birch density were also associated with the wildfire (Table 1).

Table 1.—Changes in stand density (stems/acre) over time by species group and disturbance type for Old-Series tracts in central Connecticut; for a given species group, values followed by a letter within a column were not significantly different at P < 0.05

		1927	1937	1957	1967	1977	1987	1997	2007
Oak	Fire	270	46	515	293	170	146	124	90 a‡
	Multiple	346	237	109	50	50	57	48	42 b
	Single	236	177	135	79	52	53	51	43 ab
Maple	Fire	179	67	340	310	253	213	185	159 ab
	Multiple	345	248	176	175	232	217	166	119 a
	Single	151	146	189	195	220	236	225	192 b
Birch	Fire	134	37	249	183	133	119	104	99 a
	Multi	307	203	135	142	236	277	246	198 b
	Single	241	211	171	134	125	118	108	97 a

‡Column values followed by the same letter were not significantly different at P < 0.05.

Mortality was much higher during the period of multi-year defoliations, 35-44 percent for codominant red oaks, than for the decades before or after, 5 and 3 percent, respectively (Ward 2007). The mortality pulse increased the amount of light reaching the forest floor, resulting in an increase of density as seedlings responded to the increased light and grew large enough to be measured. Surprisingly, birch density increased more than maple density, and for a longer time. In 2007, 26 years after the last defoliations, birch density was higher on the tracts that had experienced multi-year defoliations than on the tracts with other disturbance histories (F=9.250, df=2, P<0.001).

Basal Area

Stand basal area has continually increased over the past 80 years, except for the 1927-1937 period on wildfire transects and the 1967-1977 period on transects that had multiple years of defoliation (Fig. 2). In 2007, stand basal area did not differ among tracts with difference disturbance histories (F=2.183, df=2, P=0.127).

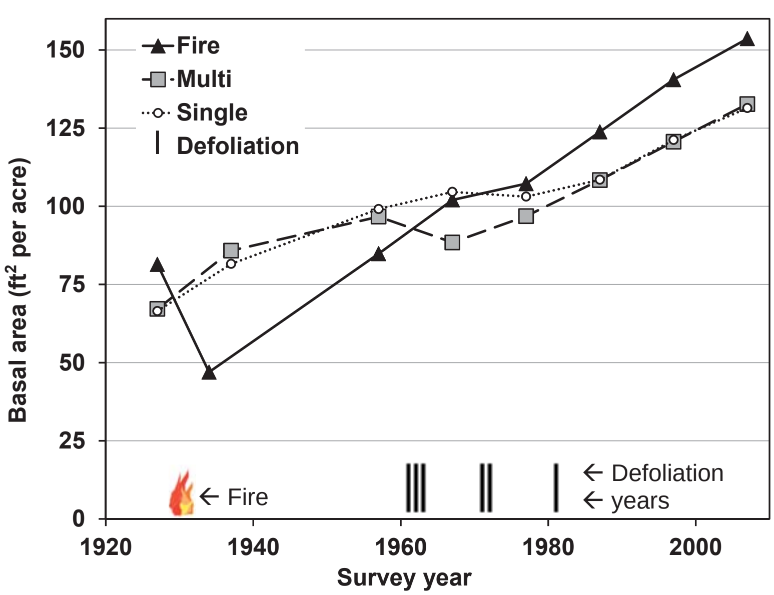

Figure 2.—Stand basal area (ft^2/acre) by disturbance type and survey year for Old-Series tracts in central Connecticut. Disturbance types: FIRE-wildfire in 1932, MULTI-repeated multi-year defoliations, and SINGLE-single-year defoliations.

Table 2.—Changes in stand basal area (ft²/acre) over time by species group and disturbance type for Old-Series tracts in central Connecticut

		1927	1937	1957	1967	1977	1987	1997	2007
Oak	Fire	32	16	40	49	47	53	63	65
	Multi	26	39	54	43	45	50	59	68
	Single	16	22	34	36	33	37	44	48
Maple	Fire	10	8	11	15	18	22	24	26
	Multi	10	11	12	14	17	18	18	17
	Single	10	11	11	13	15	17	18	19
Birch	Fire	16	13	16	20	20	22	21	23
	Multi	15	18	17	18	21	24	25	26
	Single	27	32	34	34	36	35	36	38

Repeated measures ANOVA indicated stand basal area was not independent of the interaction of survey year and disturbance type (F=10.16, df=14, P<0.001). There were distinct responses of the species groups to the different disturbance regimes (Table 2). After the 1932 wildfire, basal area of all species groups steadily increased through 2007 except for a slight decrease of oak basal area between 1967and 1977. However, while there were slight increases for maple and birch (16 and 10 ft²/acre, respectively) over the subsequent 65 years; oak basal area increased by 49 ft²/acre during the same period.

Basal area steadily increased on transects that had only single-year defoliations with a couple of temporary declines for oak and birch between 1967 and 1987. Again, the basal area increase for oak over the 80-year period (32 ft²/acre) was greater than for maple and birch (9 and 11 ft²/acre), but with less difference between species groups.

The multi-year defoliations caused a decrease of oak basal area between 1957 and 1967. During the first defoliation period, oak basal area mortality averaged 36 and 12 percent on transects defoliated by multi-year and single-year events, respectively. In addition, oak accounted for 74 percent of basal area mortality on multi-year defoliation transects compared with only 31 percent on single-year defoliation transects. Oak basal area did not recover to 1957 levels until after 1987. The increase of oak basal area over the past 20 years, 18 ft²/acre from 1987 to 2007, was greater than the total increase over 80 years for maple and birch, 7 and 11 ft²/acre, respectively.

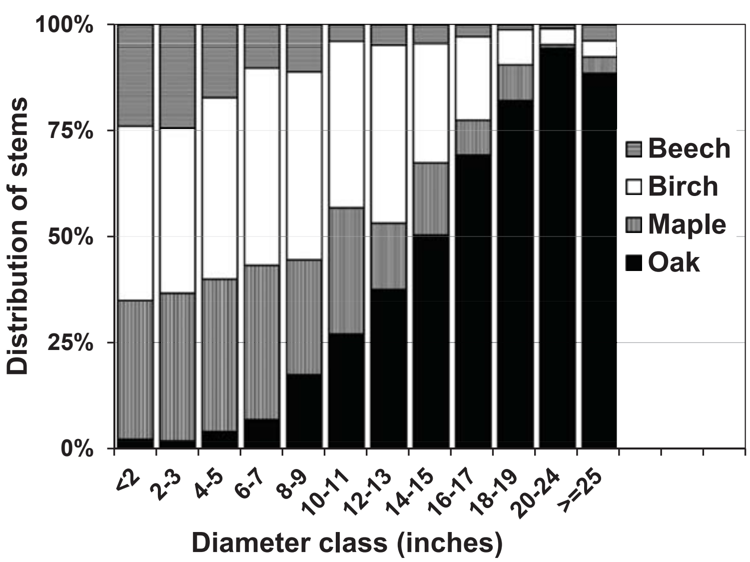

Figure 3.—Distribution of stems among diameter classes in 2007 for Old-Series tracts in central Connecticut.

In 2007, oaks were predominant in diameter classes greater than 14 inches, but were notably sparse in the smaller diameter classes (Fig. 3). Conversely, more shade-tolerant maples and beech accounted for most stems smaller than 6 inches.

Ingrowth

Ingrowth patterns were strikingly different between the three disturbance regimes over the past 80 years, but had merged to similar values of 14 to 24 stems per acre per decade (SA^{10}) by 1997 to 2007 (Fig. 4). After 1932, the wildfire transects had a sharp pulse of ingrowth to more than 500 SA^{10} between 1937and 1957 before falling to less than 50 SA^{10} in the subsequent decades. As noted above, this pulse of ingrowth was not unexpected as the wildfire killed 82 percent of stems, mostly in the pole- and sapling-size classes, providing abundant growing space for new trees (Ward and Stephens 1989).

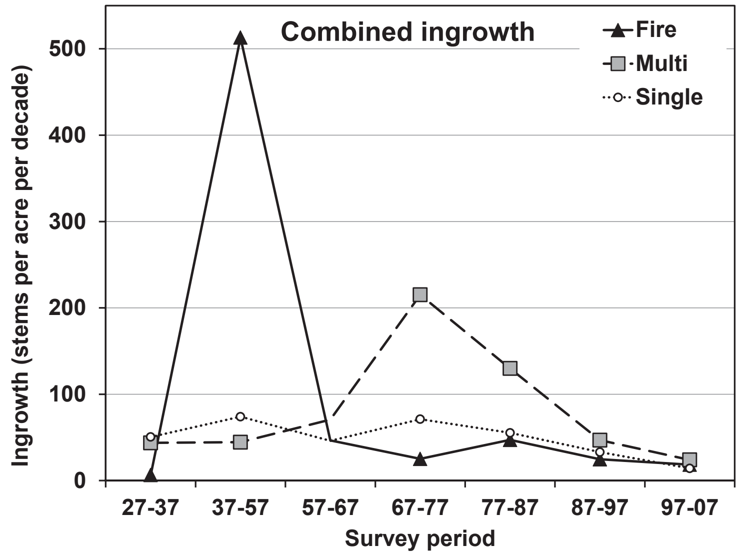

Figure 4.—Ingrowth (stems per acre per decade) by disturbance type and period for Old-Series tracts in central Connecticut. Disturbance types: FIRE-wildfire in 1932, MULTI-repeated multi-year defoliations, and SINGLE-single-year defoliations.

Ingrowth rates on transects with single- and multi-year defoliations were similar during the 1927-1967 periods. On transects that did not have a disturbance that dramatically increased mortality (i.e., single-year defoliation transects), ingrowth rates have fluctuated from 74 SA^{10} between 1937 and 1957 and 14 SA^{10} between 1997 and 2007. Mortality was much higher between 1957 and 1977 on the tracts that had multi-year defoliations than on the tract that had single-year defoliation (Stephens 1971). Similar to the wildfire, but at lower intensity and over a longer period, the increased mortality initiated by multi-year defoliations led to an increase of ingrowth from 53 SA^{10} between 1927 and 1957 to 215 SA^{10} during the 1967 to 1977 period by releasing growing space. With the appearance of the gypsy moth fungus (*Entomophaga maimaiga*) in 1989 that has mostly controlled gypsy moth (Andreadis and Weseloh 1990), increased mortality caused by large-scale defoliation ceased and ingrowth rates declined to 24 SA^{10} for the 1997 to 2007 period.

Not only did each of the three disturbance types have different ingrowth patterns over the past 80 years, the species composition of ingrowth also differed by disturbance type (Table 3). On transects that had had only single-year defoliation episodes, maple has been the predominant ingrowth species for every period over the past 80 years. Birch and maple had similar ingrowth rates before the multi-

Table 3.—Stand ingrowth (stems per acre per decade) over time by species group and disturbance type

		1927 -1937	1937 -1957	1957 -1967	1967 -1977	1977 -1987	1987 -1997	1997 -2007
Oak	Fire	0	244	11	2	15	2	1
	Multi	13	2	1	8	11	2	1
	Single	18	17	4	4	5	4	2
Maple	Fire	2	154	26	15	15	12	10
	Multi	15	23	35	85	34	12	7
	Single	20	44	29	48	39	18	7
Birch	Fire	4	114	9	9	17	12	8
	Multi	15	19	35	122	85	33	16
	Single	12	13	13	20	12	10	5

year defoliation episodes; but subsequently, birch ingrowth has been much higher than maple, 207 and 119 SA[10] between 1967 and 1987. There is also evidence that these defoliations permanently increased American beech ingrowth.

A different species response was observed on the wildfire transects where oak was the predominant species in the two decades following the fire. Other studies have also noted that oak responds well to fire (Ward and Brose 2004). Indeed, fire or a fire-surrogate such as mowing or herbicide may be necessary to obtain adequate oak regeneration (Brose et al. 2006).

DISCUSSION: DISTURBANCE AND STAND DEVELOPMENT

This study found that disturbances had long-term impacts on forest composition, especially for new ingrowth. Oak density was twice as high on transects burned by the 1932 wildfire than on unburned transects (Table 1). Maple density was highest and it was the most numerous species on transects that had had only single-year defoliation episodes. In contrast, birch density was highest and it was the most numerous species on multi-year defoliation transects. It is worth noting that the most severe disturbance (fire) was the most favorable for oak, the intermediate disturbance (multi-year defoliations) favored birch, and the mildest disturbance (single-year defoliation) favored maple.

The increasing dominance of the oak species group as measured by basal area (Table 2) and continued dominance of oaks in the larger diameter classes (Fig. 3) were predicted by development of a canopy stratified by shade tolerance (Oliver 1978, Ward and Stephens 1993). This suggests that opportunities to recruit oak regeneration will persist for several decades, if not a century, for longer lived species such as northern red and white oak; but these opportunities will not persist for shorter lived oak species, such as black and scarlet oak, that are approaching their lifespans in these 110-year-old stands (Johnson and Abrams 2009). Oak ingrowth (Table 3) and density (Table 1) have continued to decline in the absence of fire (Table 3). Consequently, oaks were a small component of both the sapling-and pole-size classes, 2 and 9 percent, respectively (Fig. 4).

Changes in disturbance regimes, specifically a decrease in fire return intervals and intensity, have been linked to conversion of oak-dominated forests to more mesophytic species in the eastern United States and Canada (Nowacki and Abrams 2008). Because short-term studies have differed on whether fire benefits oak (Brose et al. 2006), there has been a question of the utility of fire to maintain a significant oak component in hardwood forests. The single, intense wildfire in 1932 caused a pulse of ingrowth dominated by oak (Table 3). More than 70 years later, oak density on the wildfire transects was double that of transects not burned (Table 1). Another study also found that oak density was higher in areas burned 5to 51 years earlier than in adjacent unburned areas (Brown 1960). It will be several decades before fire studies established beginning in the 1990s have comparable data.

These observations indicate that maintaining oak will require active management, such as prescribed burning, mowing, or herbicide to allow development of oak regeneration competitive with maple, beech, and birch before a disturbance that removes the upper canopy (Brose et al. 2008). As noted above, partial cutting and similar disturbances such as multi-year defoliation episodes benefit non-oak species and should be minimalized in stands where management objectives include maintaining an oak component. Until there is change toward more active management and less partial cutting, oak will continue to decline and these forests will become increasingly dominated by more mesophytic species.

By contrast, increases of birch ingrowth (Table 3) and density (Table 1) were associated with mortality of upper canopy trees following multi-year defoliation episodes between 1957 and 1977. The number of trees killed by defoliation was similar to those removed during partial cutting (Ward 2007). Short-term studies (<8 years) west of the Appalachians reported that red maple dominated regeneration following defoliation induced mortality in oak stands (Allen and Bowersox 1989, Fajvan and Wood 1996, Hix et al 1991, Muzika and Twery 1995). Whether our results east of the Appalachians are specific to a local geographical region or are more representative to longer term trends will not be known until similar studies are conducted west of southern New England.

As with the shift from chestnut to oak forests in the early 1900s, the emergence of a forest dominated by mesophytic hardwoods will alter the economic, ecological, and esthetic values of the forest. The consequences of these changes will last well into the 21st century. Historically, oak has been more economically valuable than maple and birch for its higher price, lower cull rates, and higher per acre volume growth. The shift from oak will also affect many wildlife and insect populations - discriminating against those species dependent on oak and favoring those species associated with maple and birch. Changes in esthetic values are important because of increased public use of the forested landscape for both home sites and recreation. The leaves and flowers of maple and birch are more colorful than oak. However, faster growing oaks and pines are more likely to have the "big tree" characteristics that the public associates with mature forests.

ACKNOWLEDGMENTS

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FOREST ECONOMICS

DO REGION AND GENDER INFLUENCE HARDWOOD PRODUCT SELECTION?

Delton Alderman[1]

Abstract.—Consumer preference is a fundamental focus of marketing research as it is used in developing marketing strategy and the positioning of products against competitors. This study evaluated consumer hardwood preferences of consumers from three United States geographical regions, which included six different metropolitan areas. Seven hardwood species and three laminate hardwood types were assessed. Significant statistical differences in preferences were found. Results of this study could be incorporated into marketing strategies for hardwood products.

INTRODUCTION

The globalization of wood product markets during the past two decades has led U.S. consumers to use and accept species originating in other regions of the world for furniture, cabinet, millwork, and flooring products. The loss of market share for U.S. hardwood species was a contributing factor to the closure of 17 percent of U.S. hardwood sawmills between 2000 and 2009 (Buehlmann et al. 2007, Woodall et al. 2012) and a 25 to 35 percent permanent decline in hardwood processing and manufacturing capacity by the end of 2009 (Manchester et al. 2009). The principal goal of this research was to determine if expressed preferences exist for eastern hardwood species, and if so, determine how these differences may be exploited to increase markets for U.S. hardwoods.

In marketing manufactured goods, businesses and marketing professionals formulate overviews of demographic groups to create effective marketing communications. To be successful, knowledge of target markets, preferences, and traits of potential consumers within each market segment is needed. Gender and location data can provide information to develop consumer preference insights.

It has been found that women buy or influence the purchase of 80 percent of all consumer goods in the United States (Nielsenwire 2009). Women similarly influence furniture purchase decisions (Finney 2000). The purchase decisions of women may be influenced by cultural, social, psychological, and physiological perceptions. Some of these perceptions have been shown to differ between genders; men and women have different responses to blue and red light wavelengths and women have heightened sensitivity to the long-wave spectrum of light such as yellows and reds (Moss 2009). Also, a greater proportion of men are color blind (Moore 2008, Moss 2009). Women also have better memory for detailed information than men, and men tend to have better spatial ability (Nielsenwire 2009). Another gender difference is that, in the majority of all male purchases, men consistently masculinize their preferences (Gal and Wilkie 2010). Because of these various gender-based differences in perception, an objective of this study was to examine whether there were gender differences among potential consumers in expressed preferences for table tops made from seven different wood species.

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In addition, location is thought to be a relevant factor in measuring consumer perceptions of wood species as revealed preferences are considered malleable and subject to contextual influence (Eagley and Chaiken 1993). For example, consumers living in Boston may have different needs and tastes from those living in rural Virginia. From a marketing perspective, knowledge of location characteristics enables companies to target customers according to observed local preferences. Thus, the final study objective was to examine if location-based differences exist in the perceptions of potential consumers for seven species of wood.

RESEARCH OBJECTIVES

1) Discern if United States consumers have a preference for selected eastern hardwood species
2) Identify attributes, opportunities, and weaknesses of selected eastern hardwood species
3) Determine if gender differences exist in the attribute ratings assigned to the seven species by participants
4) Determine if location differences exist in the attribute ratings assigned to the seven species by participants

METHODS

To investigate a potential species' effect, we designed table tops for end tables. The tops were manufactured from the following species: black cherry (*Prunus serotina*), sugar maple (*Acer saccharum*), white oak (*Quercus alba*); foreign species included rubberwood (*Heva brasiliensis*), European beech (*Fagus sylvatica*), Lyptus®, marketed as a Brazilian cherry (*Eucalyptus grandis var. urophylla*), and American basswood (*Tilia americana*), used as a substitute for Norway maple (*Acer platanoides*). The fabricator of the table tops was unable to procure a sufficient quantity of Norway maple and after careful consideration decided to use American basswood. Table tops also were manufactured from laminate material, which included black cherry, sugar maple, and white oak. In addition, finger-jointed tables were manufactured from black cherry, sugar maple, white oak, rubberwood, European beech, Lyptus®, and basswood. We focused on species whose characteristics were in style to reduce outlier effects that would occur by including species that consumers would not consider when they decide to purchase furniture.

Attribute information was collected by a team from Virginia Tech's Pamplin College of Business, Department of Marketing by means of field studies. The focus of the field studies was to gain an in-depth understanding of raw material preferences and material attributes. Space was rented in shopping malls located in Green Bay and Madison, WI; Hyattsville, MD; Christiansburg and Norfolk, VA; and Dartmouth, MA (Table 1). The end tables were evaluated during a 1-month period, primarily on weekends. The total number of participants was 1,008. The number of male and female participants was very similar (Table 2).

Responses were collected by use of a questionnaire that consisted of three sections: (1) introduction, (2) demographic information, and (3) attribute assessment by species. Question items used a Likert scale ranging from 1 to 7 anchored by "I like it" and "I don't like it," with intervals of (1 = extremely, 2 = quite, 3 = slightly, 4 = neither, 5 = slightly, 6 = quite, 7 = extremely). Attributes rated were color, color intensity, natural blemishes, grain density, grain pattern, finish (sheen or luster), naturalness, warmness, and coldness.

Table 1.—Location and number of subjects

Site	N	Percent
Green Bay-Madison, WI	223	22.1
Christiansburg, VA	263	26.1
Hyattsville, MD	247	24.5
Newport News, VA	127	12.6
Dartmouth, MA	148	14.7
Total	1,008	100.0

Table 2.—Gender of subjects

Gender	N	Percent
Male	479	47.5
Female	468	46.4
Sub-total	947	93.9
Missing	61	6.1
Total	1,008	100.0

Several statistical techniques were used to analyze the data: independent samples t-tests, one-way ANOVA, and principal components analysis (PCA). All statistical techniques used a significance level of alpha = 0.05. SPSS® (2009) 18.0 was used for all analysis. PCA was used for data reduction to simplify the data by reducing a large set of variables to a lesser number for analysis. In the results, attribute factor loadings of 0.7 or greater were retained for further analysis. The rationale is that this level corresponds to about one-half of the variance in the questionnaire item being elucidated by the factor.

RESULTS

The highest rated species, in terms of visual preference, were Lyptus®, black cherry, white oak, and European beech, respectively. Analysis revealed there were no statistical differences between gender among and between the species ($\alpha = 0.05$); location differences were discerned. The lowest rated species/products were the laminates and American basswood. Of note is the similarity of the Lyptus® and cherry ratings. The Lyptus® boards were specifically selected to be contrasted against cherry. Another contrast investigated was between white oak and European beech; as in the previously mentioned pair, the ratings for the latter two species also were similar (Table 3.)

Willingness-to-pay entails a subject's dollar value estimate of what she or he would pay for a discrete table top. Willingness-to-pay also can be considered a proxy for overall species judgments, as similar findings to the overall evaluative ratings were discerned. Lyptus® and black cherry were the species that the subjects indicated they would pay most to purchase and were statistically significant ($p = 0.001$) from other species, as were white oak and European beech (Table 4). No other statistical differences were discerned in the willingness-to-pay evaluation.

Table 3.—Overall rating means and standard deviations for each species

Species	N	Mean ($\bar{x}$)	S. D.
Lyptus®	994	2.11	1.45
Cherry	988	2.41	1.55
White oak	991	2.80	1.66
European beech	984	2.88	1.46
Sugar maple	987	3.04	1.57
Rubberwood	995	3.11	1.68
Cherry laminate	988	3.23	1.85
Basswood	984	3.35	1.62
Maple laminate	985	4.19	1.92
White oak laminate	984	4.78	1.90

Table 4.—Overall species price means and standard deviations: willingness-to-pay for a table produced from a particular species

Species	N	Mean ($\bar{x}$)	S. D.
Lyptus®	902	131.75	127.99
Cherry	916	120.47	122.89
White oak	910	102.10	108.58
European beech	897	91.21	100.85
Sugar maple	904	89.93	98.34
Rubberwood	912	89.36	101.97
Cherry laminate	903	86.70	103.67
Basswood	902	82.75	97.52
Maple laminate	905	63.99	86.76
White oak laminate	898	54.13	79.36

SPECIES ANALYSIS AND DISCUSSION

Lyptus®

Lyptus® was the highest rated species or product. Of note were the ratings for color ($\bar{x}$ = 2.00), color intensity ($\bar{x}$ = 2.04), a natural look ($\bar{x}$ = 2.27), and warmness ($\bar{x}$ = 2.16). Subjects valued Lyptus® most highly in pricing and potential purchase. Statistical differences were not found between genders nor locations for the overall rating or for any of the nine specific appearance attribute ratings. From a marketing promotion perspective, this finding suggests that market segmentation by gender or location is unnecessary.

Black Cherry

The second highest rated species or product was black cherry. Important ratings were discerned for color ($\bar{x}$ = 2.30), color intensity ($\bar{x}$ = 2.41), natural look ($\bar{x}$ = 2.42), and warmness ($\bar{x}$ = 2.42). Although cherry was rated somewhat lower than Lyptus®, the ratings for natural look, warmness, and coldness were very similar. Again, no statistical differences in preference were found between the genders or locations for the attribute ratings for this species.

White Oak

White oak was the third highest rated species; key ratings were color ($\bar{x}$ = 2.86), color intensity ($\bar{x}$ = 2. 86), natural look ($\bar{x}$ = 2.63), and warmness ($\bar{x}$ = 2.79). The color ($p = 0.003$) and color intensity ($p = 0.01$) rating means were statistically different for gender, suggesting that market segmentation by gender should be considered, because males may prefer a light, grainy appearance found in white oak. Thus, this may present a product positioning opportunity for white oak. Statistical differences were not found for location.

European Beech

The fourth highest rated species or product was European beech. Important attribute ratings were similar to white oak: color ($\bar{x}$ = 2.77) and color intensity ($\bar{x}$ = 2.84). No statistical differences for color were found between genders or locations. A statistical difference was discerned between males and females for color intensity ($p < 0.01$), suggesting that promotional efforts should emphasize color intensity for women, if the product is manufactured to emphasize this attribute.

Sugar Maple

Sugar maple was the fifth rated species or product. Color ($\bar{x}$ = 3.06) and color intensity ($\bar{x}$ = 3.18) were the top two attributes noted by the subjects for this species, but they both received nearly neutral (3.5 on a 7-point scale) ratings. There were no statistical differences found between gender or locations for color and color intensity, signifying that market segmentation by gender or location is unnecessary.

Rubberwood

Rubberwood was the sixth highest rated species or product. Color ($\bar{x}$ = 3.12) and color intensity ($\bar{x}$ = 3.10) were rated near neutral. Statistical differences between genders for color ($p = 0.01$) and color intensity ($p = 0.05$) were found; men preferred rubberwood's color more than women, suggesting that businesses should consider treating the color of rubberwood as a segmentation and positioning factor.

Regarding location, several statistical differences were discerned for rubberwood in color and color intensity. In the color analysis, differences were found between Green Bay-Madison and Christiansburg ($p < 0.01$), Green Bay-Madison and Hyattsville ($p < 0.01$), and Green Bay-Madison and Dartmouth ($p < 0.01$). For color intensity, statistical differences were found between Green Bay-Madison and Christiansburg ($p = 0.05$), Green Bay-Madison and Hyattsville ($p < 0.01$), and Green Bay-Madison and Dartmouth ($p < 0.01$). Again, these findings indicate color and color intensity are attributes that can be used in marketing segmentation and product positioning.

CONCLUSIONS

Gender and location differences were found to exist in the rating of various appearance attributes associated with seven species of wood manufactured into table tops. Differences related to color and color intensity were more commonly based on gender than on location. According to recent research, "Women notice nuance," said Jennifer Ganshirt, who was interviewed for a 2008 article in Dynamic Graphics +Create magazine (Moore 2008). In gender marketing, color is important, because color may create a distinct and subconscious response (Gunelius 2011). Thus, the practical implications for marketing strategy, marketing communications, product positioning, and marketing tactics are evident. Products should be marketed to women differently for several reasons: (1) women make an estimated 80 percent of all furniture purchases (Finney 2000); (2) women are more color precise and detect even a slight change in color (Gunelius 2011); and (3) a greater proportion of men are color blind (Moore 2008, Moss 2009). Hardwood producers and manufacturers, retail stores, and marketers should specifically strategize about how they may best appeal to women. Firms should endeavor to get wood products and design (which also includes color), marketing communications, and other product characteristics in sync with how the female subconscious mind receives and processes information. This may greatly increase marketplace success.

From a marketing perspective, knowledge of location preferences and consumer characteristics enables marketers to target customers according to actual local preferences in real time. In this study, one species produced a statistical location difference, rubberwood. Logically, it would seem that there are other species that would produce a similar result. One tactic is to present detailed product information (i.e., species, origin, sustainability, and color). From this, a retailer may be able to create repeat customer visits and word-of-mouth marketing.

STUDY LIMITATIONS

The lumber used in the fabrication of the table tops was not stained; rather the table tops were built from the material as received, with only a clear coating applied. We chose not to stain the wood due to the many different types of stains available since we did not have enough funding to conduct research on all combinations of species and stain. Finally, this study represents a snapshot in time of U.S. consumers and can be expected to change over time given societal shifts in priorities and fashion sense.

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THE INFLUENCE OF TRADE ASSOCIATIONS AND GROUP CERTIFICATION PROGRAMS ON THE HARDWOOD CERTIFICATION MOVEMENT

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Abstract.—Forest certification has gained momentum around the world over the past two decades. Although there are advantages to being certified, many forest landowners and forest products manufacturers consider forest certification of U.S. forest and forest products unnecessary. Many believe that U.S. forests are already sustainably managed, the current certification systems are not trustworthy, and certification programs, in their current state, are too costly. To promote the sustainability of U.S. forests and address issues that landowners and forest products manufacturers have with certification, governmental agencies, trade associations, and environmental agencies have become involved in the certification movement. These organizations assist landowners and manufacturers by creating group certification programs and providing information and tools necessary to obtain certification. In 2009, a study was conducted to determine how the involvement of governmental agencies, trade associations, and environmental agencies influenced the certification movement. Research was conducted through a mail-based survey to 1,239 primary hardwood manufacturers in the Appalachian Region and through case studies of the Appalachian Hardwood Manufacturers Inc., (AHMI) Association, the National Wood Flooring Association (NWFA), and the Wisconsin Department of Natural Resources. Results indicated that these entities were instrumental in increasing the awareness of certification and providing the tools their members need to become certified. Through the programs implemented by these entities, the supply of certified raw material and the number of certified forest products manufacturers has increased.

INTRODUCTION

Loss of forests and forest resources has long been a concern of societies around the world. Decades ago, these concerns led to the implementation of forest certification. There are currently two types of forestry certificates: sustainable forestry management certificates and chain of custody (COC) certificates (Anderson et al. 2005). Sustainable forestry management certification is the process of verifying that forests are planted, grown, or harvested according to the standards of the certifying system (Anderson et al. 2005). Chain of custody certification is the process of tracking a forestry product back to the forest source and enables forest producers to verify that their products are made from raw materials produced in a sustainably managed forest (Anderson et al. 2005, Hansen and Bratkovich 2000). Although the forest certification practices began as a way to protect tropical forests in developed/underdeveloped countries, it is primarily practiced in developed countries (Cashore et al. 2005, Kollert and Lagan 2007). Even though most certified forest lands are in developed countries, the certification movement has met much resistance.

In the United States, many forest landowners and forest products manufacturers believe certification of U.S. forests and its products is unnecessary. They do not trust the certification programs, and many believe that forest certification only exists to make a profit. In addition, many landowners

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and manufacturers believe the current certification systems are too costly for them to participate in (Butterfield et al. 2005, Rickenbach 2002).

To address these issues and promote the sustainability of U.S. forests, governmental agencies, environmental agencies, and forest products trade associations have become involved in the certification movement. These organizations have stepped in to assist landowners and manufacturers by creating group certification programs and providing information and tools necessary to obtain certification. Numerous studies have been conducted on small family landowner cooperatives/ group certification (Blinn et al. 2007, Cordell and Tarrant 2002, Hull and Ashton 2008). Other studies have shown the positive impact of government assistance and trade association involvement on business operations (Howard 1990, Kittredge 2003, Stoddard 1964). However, there has been little/no research on the effect of governmental and trade association involvement on the decision to pursue certification. Only two articles related to this subject were found in the literature (Klooster 2005, Segura 2004). Both articles showed that governmental and nongovernmental organizations could have a positive effect on forest certification/sustainable management participation.

To fully understand certification as it applies to the hardwood industry, it is important to understand the key factors that affect the decision to pursue certification. The objectives of this research were to (1) determine if association membership affects pursuance of certification, and (2) investigate and describe the dynamics of forest certification programs aimed at certifying groups of forest landowners.

STUDY AREA

To understand certification and the U.S. hardwood industry, one component of this study focused on primary hardwood manufacturers in the Appalachian Region, which encompasses most of the hardwood production in the United States. The perimeter of the Appalachian Region was set according to the boundaries that the Appalachian Hardwood Manufacturers Association, Inc. (AHMI) uses to define its membership region. This region includes 344 counties in New York, Pennsylvania, Ohio, West Virginia, Maryland, Virginia, Kentucky, Tennessee, North Carolina, Alabama, Georgia, and South Carolina. A list of primary hardwood manufacturers in these regions and their contact information was compiled using listings from association bulletins, state directories, governmental documents, and other resources. The survey population was made up of all primary hardwood solid wood products manufacturers identified in these information sources.

A broader region was used in the case study component of this research. The Appalachian Hardwood Manufacturers Association, the National Wood Flooring Association (NWFA), and the State of Wisconsin Department of Natural Resources (DNR) were selected for case studies. AHMI represents a primary hardwood association whose members are responsible for a large percentage of primary hardwood production. NWFA is an association that represents a secondary industry whose members are responsible for a large percentage of hardwood flooring production. The Wisconsin DNR is the forerunner in state-implemented group forest certification.

METHODS

To meet the objectives of this section of the study, research was conducted through both a mail-based survey[2] and case studies.

Survey Methods

A mail-based survey was developed using Dillman's Tailored Design Method (Dillman 2000), methods adapted from Gilbert Churchill's Procedures for Developing a Questionnaire, (Churchill 1999), and other published certification related surveys. The questionnaire was divided into three sections. Section 1 contained demographic questions about the responding company. Section 2 contained questions about the company's beliefs and attitudes on chain-of-custody certification. Section 3 contained questions about the decision process that a manufacturer uses when deciding whether to provide chain-of-custody certified products.

In October 2008, the initial survey was mailed to 1,239 primary hardwood manufacturers. Four weeks after the initial survey was mailed, a followup questionnaire was mailed to those manufacturers who had not yet responded. After the initial and follow-up letters were mailed, it was necessary in some cases to call manufacturers to determine if addresses were correct or if they were still in business.

Of the 1,239 questionnaires mailed to Appalachian primary hardwood manufacturers, 254 were either returned with bad addresses or returned indicating that the business was closed or was not a primary hardwood producer. Of the remaining 985 questionnaires, 192 were returned completed and were deemed usable for the study; this represents an adjusted response rate of 19 percent.

To ensure that the study's results are valid, nonresponse bias was estimated by comparing early respondents to late respondents as per Armstrong and Overton (1977). Manufacturers who responded before the second mailing were classified as early respondents, whereas those responding after the second mailing were classified as late respondents.

Using nonparametric and parametric statistical analyses, we found no significant differences between early and late respondents. Frequency analysis was conducted on all variables in the survey. The results of early and late respondents were compared to determine if any significant differences were found. The results were equally distributed between both groups. To further test for nonresponse bias, a Kruskill-Wallis test was performed on the certification status of early and late respondents to determine if any significant differences existed. At $\alpha = 0.05$, the test returned a p-value of 0.45. No significant difference was found. Because meaningful differences between the two groups were not found, nonresponse bias should not present a serious problem (Rainer and Harrison 1993).

To better understand the relationship between trade association membership and certification adoption, it was important to examine attitudes of association members toward certification. Respondents were asked to rate their level of agreement or disagreement with a number of statements about chain-of-custody (COC) certification. To measure the respondents' level of agreement, the Likert method of summated ratings was used (Likert 1932). Respondents were asked to indicate their

[2]The survey was conducted by the Warnell School of Forestry and Natural Resources at the University of Georgia.

level of agreement with 18 certification statements by marking the number that best corresponded with their attitude surrounding the statement: 1 = strongly disagree to 5 = strongly agree.

The attitude of association members and nonmembers was then compared to determine if any differences existed. The mean and standard deviation of the responses to each statement were calculated. The responses from each group were analyzed and compared using a Wilcoxon test to see if differences existed.

Case Study Methods

Because this study examined the role of various organizations in the certification movement, it was necessary to obtain first-hand accounts from individuals in these organizations. According to Seidman (1991), the primary way for a researcher to investigate an organization, institution, or process is by interviewing the individuals who make up the organization or carry out its processes. Case studies can help identify and understand the relationships and views of the subjects studied (Thacher 2006). For this reason, case studies were used to further examine the relationship between association membership and certification. Two trade associations (one representing primary manufacturers and one representing a secondary hardwood industry) and one group certification program were chosen on which the case studies were based.

Personal open-ended interviews were conducted with Tom Inman, President of the Appalachian Hardwood Manufacturers Inc., (AHMI) Association; Edward Korczak, Executive Director of the National Wood Flooring Association (NWFA); and Paul Pingrey, Forest Certification Coordinator for the Wisconsin DNR. Additional interviews were conducted with Ed Dallison (AHMI member and President of Dallison Lumber), Donald Finkell (NWFA member and President of Anderson Hardwood Floors), and Terry Mace (Forest Utilization and Marketing Specialist with the Wisconsin DNR). Supplemental data also were collected through Web resources.

Because this research sought to investigate the relationship between trade associations/group certification programs and the certification movement, the case studies are exploratory and descriptive in nature. Information obtained from the interviews was recorded (with permission) and analyzed for cause and effect relationships.

RESULTS

Certification and Trade Association Membership Status

To address the objectives of this study, it was important to determine the certification and trade association membership status of the respondents. Respondents were given a choice of five different certification levels to describe their current certification status: (1) certified and intend to remain so; (2) certified, but not sure about recertification; (3) not certified and not currently considering certification; (4) not certified, but actively seeking certification; (5) and not certified, but somewhat interested. Of the 192 respondents, 186 indicated their certification status. For this study, these respondents were then classified into two categories: certified and noncertified. After classification, there were 40 certified respondents and 146 noncertified respondents.

Table 1.—Association between trade association membership and certification adoption

		Nonmember	Member	Total
Certified	Frequency	12	28	40
	Expected	18.495	21.505	
	Cell Chi-Square	2.2807	1.9614	
	Row Percent	30.00	70.00	
Noncertified	Frequency	74	72	146
	Expected	67.505	78.495	
	Cell chi-square	0.6248	0.5374	
	Row percent	50.68	49.32	
	Total			186

Statistic	DF	Value	Prob
Chi-square	1	5.4043	0.0201

Respondents were then asked if they were a member of a trade association. If the respondent indicated "yes," they were asked to list the associations they had memberships with. Of the 192 respondents, 186 indicated their membership status. Fifty-four percent (102) of the respondents indicated they were members of a trade association. More than 50 percent (55) of the respondents who indicated they were members of a trade association held membership in multiple associations. Appalachian Hardwood Manufacturers, Inc., National Hardwood Lumber Association, National Wood Flooring Association, and Kentucky Forest Industries Association were some of the association memberships listed.

Trade Associations and Certification Relationship

To determine if membership in a trade association had an effect on the decision to pursue certification (two-sided test), a chi-square test was performed to determine if there was a relationship between trade association membership and certification status. The p-value of the chi-square was 0.020. Therefore, it was concluded that at the 0.05 significance level there was a relationship between certification status and association membership. The results indicate that members of trade associations are more likely to pursue certification than nonmembers.

Results indicated that differences existed between the attitudes of the two groups. The result from the tests for the two different groups and the differences between the two groups are shown in Table 1. When comparing the responses of association members to the responses of nonmembers, numerous differences were found. Although association members tended to be more positive toward the statements than nonmembers, both groups overall had primarily negative feelings toward the certification statements. Of the 18 statements, responses between the two groups were statistically

Table 2.—Ranking of certification statements by association membership status and statistically significant differences (1=strongly disagree, 5=strongly agree)

Statement	Mem. obs. (n=)	Mean/ std. dev.	Non-mem. obs. (n=)	Mean/ std. dev.	Sig. diff.
Our company is environmentally conscious	102	4.37/.81	84	4.35/.88	
Our company is familiar with the certification process	101	3.58/1.27	80	2.69/1.37	**
Our company has purchased environmentally certified wood in the past year	99	2.48/1.72	76	2.00/1.38	
Our company plans to be certified next year	94	2.59/1.58	75	1.59/1.16	**
Our company believes that the chain-of-custody certification process is complicated	99	3.47/1.35	76	3.26/1.60	
Our company believes certification is necessary to be competitive	99	2.70/1.35	79	2.04/1.20	**
Our company believes certification has environmental benefits	100	2.63/1.35	79	2.34/1.35	
Our company believes certification is necessary	100	2.58/1.15	80	1.94/1.05	**
Our company believes certification has financial benefits	98	2.39/1.30	80	1.96/1.13	*
Our company seeks suppliers of environmentally certified wood products or raw materials	98	2.10/1.37	77	1.53/.94	**
Our company believes the benefits of certification are worth the costs	101	2.19/1.19	80	1.80/1.12	*
Our company feels pressured by our customers to supply certified wood	99	2.32/1.23	78	1.81/1.18	**
Our company feels pressured by outside groups (other than customers) to produce environmentally certified products	99	2.12/1.50	79	2.13/1.36	
Our company cannot find an adequate supply of certified wood to justify our becoming certified	95	2.91/1.50	75	2.67/1.57	
Our company only buys certified wood when there is a demand	98	2.07/1.35	77	1.60/1.07	*
Our company believes consumers will pay a premium for certified wood products or raw materials	99	2.05/1.14	82	1.94/1.26	
Our company always purchases certified wood	98	1.57/1.05	78	1.51/1.03	
Our company will pay a premium for certified wood products or raw materials	100	1.70/1.03	79	1.38/.90	**

*significant at α = 0.05, ** significant at α = 0.01

different for 10 of the statements. Only two statements received positive ratings by both groups. Both groups agreed to strongly agreed (rating more than 4 but below 5) with the statement "Our company is environmentally conscious" and slightly agreed to agreed (rating more than 3 but below 4) with the statement "Our company believes that the chain-of-custody certification process is complicated."

From Table 2 it can be seen that, for 7 of the 10 significantly different responses, the responses were different at α = 0.01. Although both groups disagreed that certification had financial benefits, nonmembers seemed to disagree more strongly than association members (a mean rating of 1.96). Nonmembers also disagreed more strongly with the statements "Our company believes the benefits of certification are worth the cost" and "Our company only buys certified wood when there is a demand" (mean ratings of 1.80 and 1.60, respectively).

Table 3.—NWFA RPP fees for each membership division

Tiers	Tier guidelines	Fees
Tier 1	Must procure raw materials from sources that have been NWFA verified sustainable Must verify that raw materials originating from a country listed as high-risk for illegal logging meets NWFA's verified sustainable guidelines In program for 3 consecutive years	Annual SCS audit fees
Tier 2	Must agree to obtain FSC COC certification Must actively manufacture FSC products and/or trade and actively increase sales of certified products Must join the FSC Procurement Group and meet FSC controlled wood standards for all their non-FSC wood supply In tier for 2 years or program for 5 consecutive years	Based on annual sales: Companies with annual sales of: $0-20 million pay $2,000/year $20-49 million pay $3,500/year $50-99 million pay $5,000/year over $100 million pay $7,500/year
Tier 3	Must meet RPPs benchmarks for 3 or more years without interruption Must ensure that FSC certified product sales constitute 50 percent or more of overall company sales in a single year	Same as Tier 2

Some of the differences between association members and nonmembers may be a direct result of the increased knowledge obtained through membership networking. Association members slightly agreed to agreed with the statements "Our company is familiar with the certification process" (a mean rating of 3.58). Nonmember respondents tended to disagree with this statement (a mean rating of 2.69). Because of the emphasis that forest products associations have placed on certification in the last decade, it was expected that association members would be familiar with the certification process. Nonmembers may not have access to the information networks provided by trade associations. Several respondents indicated being unfamiliar with the certification process, and two indicated they had never heard of COC certification.

CASE STUDY RESULTS

Appalachian Hardwood Manufacturers, Inc. (AHMI)

Appalachian Hardwood Manufacturers, Inc. (AHMI) is a forest products trade association headquartered in High Point, NC (AHMI 2009). It was founded in 1928 to promote logs, lumber, and wood products from the Appalachian Mountain Region. The association has 204 corporate members and encompasses 344 counties in 12 states. In this region, there are currently 110.2 million acres of privately owned forest (AHMI 2009). The Appalachian hardwood industry is an important component of the region's economy, and AHMI's mission is to assist producers, manufacturers, suppliers, and consumers in making the best decisions for their hardwood needs. The association is made up of five divisions: producer, distributor, forestry, consumer, and supplier (AHMI 2009).

Any individual or company is free to join AHMI as long as the requirements defined by the association's bylaws are met. Depending on the membership division, the cost to join AHMI ranges from $100 to $12,000/year (Table 3) (AHMI 2009). The membership dues are paid monthly by members in the producer division and annually by all other members. As members of the AHMI trade association, individuals and companies are provided with services to help them promote their businesses and products. Yearly, AHMI holds workshops and seminars that are specific to current industry issues. The association also provides its members with media training and marketing/promotional materials to help members remain competitive and be successful.

Certification

Because certification has been a major issue facing the hardwood industry, AHMI has sought ways to promote the Appalachian Region's sustainable hardwoods. In 2006, AHMI created the Verified Sustainable Program to verify and promote the sustainability of the Appalachian hardwood timber resource. According to the U.S. Department of Agriculture's Forest Inventory and Analysis (FIA) research data, the annual timber harvest levels in the 344-county Appalachian hardwood region have been substantially less than net annual growth for more than 50 years. In fact, the net annual timber growth in the region exceeds annual harvest levels by more than 2.29 to 1. By the definitions set forth by AHMI, the current hardwood harvest rates in the Appalachian Region are sustainable.

The Verified Sustainable Program, implemented in 2007, is provided to AHMI members as a membership benefit. Members pay only for certificates documenting sustainability and other promotional materials. Certification is not related to individual timber tract sustainability but to the sustainable harvest rate for an entire region. The program provides its members with documentation that the wood and products they produce are verified sustainable. This program helps meet the demands of the customers of some members who are looking for sustainable hardwood products. However, in some cases, customers do require Forest Stewardship Council (FSC) and/or Sustainable Forestry Initiative (SFI) certification. Recently, the association has begun working to provide group certification to those members who desire FSC/SFI certification.

In 2007, when AHMI first began the implementation of the Verified Sustainable Program, only 17 members chose to participate. However, in 2008, 59 additional members joined the program. To date, AHMI has 107 members that participate in this program (with several more joining in 2009). According to AHMI President, Thomas Inman, the Verified Sustainable Program has helped fill a void in the certification program. In a system where manufacturers were either fully certified or noncertified, AHMI has created a middle-tier certification system. Members who were unable to obtain certification from "top-tier" certification schemes such as SFI and FSC (because of cost and lack of supply) or who felt like these certifications were unnecessary for them can now provide their customers with certified sustainable products through the Verified Sustainable Program.

Member Perspective

According to Ed Dallison, President of Dallison Lumber, Inc., being a member of the AHMI trade association has helped his company gain knowledge of the certification movement and process. Dallison Lumber Inc., a family owned company in Jacksonburg, WV, has been in business for more than 125 years. The company produces more than 5 million board feet of Appalachian hardwood each year and supplies lumber, timbers, railroad ties, post and beams, and bridge materials to the eastern and mid western portions of the United States (Dallison Lumber, Inc. 2009).

Although the company first heard of forestry certification 3 to 4 years ago, Dallison admits that he paid no attention until his customers began demanding certified lumber. About a year ago, Dallison Lumber obtained FSC forest and COC certification. The company currently co-owns 20 acres of land with a local concentration yard from which it supplies roundwood to meet demand for certified lumber. Annually, the company produces around 1.5 thousand board feet (MBF) of certified hardwood and supplies 10 companies with COC certified lumber. According to Dallison, the cost of certification is high, but because the selling of certified lumber is easier, the company has been able to realize a small premium. Dallison believes AHMI has been beneficial in helping him understand certification and has provided him with certification alternatives.

National Wood Flooring Association (NWFA)

The National Wood Flooring Association (NWFA), a wood flooring trade association headquartered in Chesterfield, MO, was founded in 1985 by a group of leading wood flooring professionals who saw the need for an association that would promote the wood flooring industry and address industry-specific issues. NWFA currently has more than 4,000 corporate members in 55 countries. The membership is made up of manufacturers, dealers, distributors, and installers of wood flooring. The association spends most of its time on education and marketing programs and on programs that assist in the commercial advancement of wood flooring products. At the time of the interviews, the association's Executive Director/CEO was Edward Korczak. The Executive Director/CEO oversees a staff of 25 and is instrumental in developing many of the association's key programs

Any individual or company is free to join NWFA as long as they meet the requirements as defined by the association. The association has a unique system for dues and charges: one set price ($395/year) for membership regardless of an individual's membership category. As members of NWFA, individuals and companies are provided with services to help promote their businesses and products. The association provides its members with certification training. In addition to workshops and seminars held annually to keep members informed, the association also publishes Hardwood Floor seven times a year (NWFA 2009).

Certification

In 2008, to meet the demand for domestically produced certified wood flooring, NWFA introduced the Responsible Procurement Program (RPP). NWFA realized that its members could not meet the demand of the U.S. Green Building Council and other organizations that required FSC certified wood. If FSC certified flooring was demanded, manufacturers would have to import flooring from foreign countries. The program was initiated by contacting the U.S. Forest Service. The Forest Service's Forest Inventory and Analysis (FIA) data were used to determine that 33 states had sustainable hardwood harvests.

Using this information, NWFA developed a three-tier certification program. RPP is open to all NWFA members and is voluntary. The independent third-part auditing firm, Scientific Certification Systems (SCS), oversees the program. The members pay for the cost of the program with annual participation fees based on the company's sales levels (Table 3).

Tier 1 of the program verifies that members manufacture wood flooring from raw material originating from NWFA-verified sustainable U.S. forests. Manufacturers must procure wood from the 33 states in which hardwood harvests have been verified sustainable (growth exceeds removals based on FIA data). If manufactures use or import raw materials originating from a country listed as high-risk for illegal logging, they must enroll in the NWFA Verified Legal Program that uses NWFA-approved organizations to verify wood used or imported meets NWFA's verified sustainable guidelines. Companies that participate in the NWFA COC system and meet the defined requirements are entitled to use the "NWFA Verified Sourced from U.S. Renewing Forests" and the "NWFA Verified Legal Imported" labels on their products. After 3 years of participation in and meeting the requirements of Tier 1, members are expected to advance to Tier 2 and meet the Tier 2 requirements.

Tier 2 is the intermediate level of the program. To participate in this tier, members agree to obtain FSC COC certification. The company must actively manufacture and/or trade FSC certified products and actively increase its sales of FSC certified products over time. The company also must join the FSC Procurement Group, led by NWFA and NWFA member companies. The group works closely with organizations such as FSC Family Forest Alliance to make FSC certification more attractive to small private landowners across the hardwood region. If the company meets FSC controlled wood standards for all their non-FSC wood supply after 2 years in Tier 2 or 5 years in the program, they advance to Tier 3.

Tier 3 is the highest level of achievement in the NWFA's Responsible Procurement Program. This tier is reserved for those members who meet all of the requirements for Tiers 1 and 2. They must meet RPP's benchmarks for 3 or more years without interruption. To participate in this tier, members must ensure that FSC certified product sales constitute 50 percent or more of overall company sales in a single year (an aggressive goal).

Since implementation of the program in December 2008 (just 3 months before this interview was conducted), 24 companies have shown interest in participating. Of those 24 companies, four have signed the RPP license of agreement and have begun the process to become a member of the program. The remaining 20 companies have requested the RPP license of agreement and are in the process of reviewing it with legal counsel. According to Korczak, these 24 companies represent 70 percent of the industry's domestic hardwood flooring production. Korczak believes the interest and participation of these 24 companies will help build further program interest (i.e., many of these companies are opinion leaders). He also believes that NWFA's promotion of the program through meetings, video newsletters, trade shows, and mailings will generate additional interest in the program.

Member Perspective

According to Donald Finkell, President of Anderson Hardwood Floors, Inc., NWFA has been beneficial to the hardwood flooring industry. He feels the association's Responsible Procurement Program will have the biggest impact on members with small manufacturing facilities. Anderson Hardwood Floors, founded in 1946 and headquartered in Clinton, SC, will be the first member company to enter NWFA's Responsible Procurement Program. Anderson's product line ranges from wood flooring produced from domestic species such as oak and pine to flooring produced from exotic species such as bamboo (Anderson Hardwood Floors 2009). The company is a leading innovator in the wood flooring industry and is responsible for developing the 5-ply construction method used to create wood flooring. The company also is responsible for providing consumers the first "no wax" maintenance free flooring (Anderson Hardwood Floors 2009).

Because Anderson is a leading innovative producer in the industry, it is not surprising that the company would be one of the first flooring manufacturers to participate in NWFA's innovative Responsible Procurement Program. The company also has a plant in Paraguay and believes this program will help members who have foreign imports to meet the provisions of the Lacey Act (which prohibits the import of illegally harvested or traded timber). Finkell admits that residential consumer demand for certified flooring is essentially non-existent. However, there is a small demand from commercial LEED-projects that must have FSC certified flooring. Through the efforts of NWFA, Finkell hopes to see an increase in the supply of certified hardwood raw materials and products.

The State of Wisconsin

The Division of Forestry of the Wisconsin Department of Natural Resources was founded in 1904, under the guidance of E.M. Griffith, Wisconsin's first Chief State Forester. He was an early leader in developing state forestry programs that have shaped Wisconsin forestry over the past 100 years (Wisconsin DNR 2009). The Division of Forestry is made up of three bureaus and one office: the Bureau of Forest Protection, the Bureau of Forest Management, the Bureau of Forestry Services, and the Office of Forest Sciences. Wisconsin has 16 million acres of forest land that the Division of Forestry regulates, protects, and helps to manage. Of this amount, 70 percent is privately owned forest land (Wisconsin DNR 2009).

Forests are important to the State of Wisconsin. These lands provide habitat for hundreds of plants and animals and provide individuals with a social outlet. Wisconsin's forestry resources also play an important role in the state's economy. More than 1,850 wood-using companies produce nearly $20 billion of forest products each year, and more than 300,000 individual jobs in the state rely on the forest products industry (Wisconsin DNR 2009). For this reason, Wisconsin has been active in the sustainable management of its forestry resources.

Certification

In 1985, Wisconsin enacted the Managed Forest Law (MFL) as an incentive to encourage sustainable forestry on privately owned forest land (Wisconsin DNR 2009). Through the law, the open-enrollment program reduces and defers the property taxes of landowners that manage lands according to MFL sustainable management plans. The program is open to all private landowners that own 10 to 2,470 acres of forest land. According to Paul Pingrey, Forest Certification Coordinator for the Wisconsin DNR, the program was originally based on U.S. Forest Service stewardship guidelines and gives landowners a 75 to 95 percent reduction on their property taxes. Each plan is developed considering and evaluating several natural resource elements, such as water, aesthetic quality, timber, forest health, and threatened and endangered species. At the onset of the program, 42,826 landowners were enrolled.

In 2003, Wisconsin began to explore third-party certification of its forest lands. In 2005, the MFL program received full certification endorsement from the American Tree Farm System (ATFS). MFL members were automatically enrolled in the ATFS certification, but were allowed to opt out at any time. Because of the endorsement, 500 members of the MFL program decided to opt out of the ATFS certification option. Although companies such as Time, Inc. were happy with ATFS certified raw materials, others preferred FSC. Because of these requests, a full FSC study of forest in the MFL

Table 4.—Major land management programs administered by the Wisconsin DNR

Land management program	Certified acreage
Wisconsin State Forests	517,734 acres
Wisconsin DNR Land Division	1,080,675 acres
Wisconsin County Forests	2,353,897 acres in 27 counties
Managed Forest Law	2,239,205 acres under 41,875 orders with private landowners
Total	6,191,511 acres

program began in March 2008. By December 2008, MFL had received full FSC endorsement. After FSC's endorsement, an additional 461 members decided to opt out of the FSC group certification option. Pingrey believes that most landowners decided to opt out because of FSC's pesticide restrictions and the fear that certification costs would eventually fall on them.

To date, the MFL certification group has 41,865 family forest members that own 2.2 million acres of FSC and ATFS certified land (22% of all Wisconsin's privately owned nonindustrial forests). As a part of the program, members do not pay to be certified. The state pays the certification costs, which is a total of $76,585 for a 5-year SmartWood audit contract. Wisconsin pays less than $2 per landowner for certification, allowing it to realize certification economies of scale.

In addition to the MFL program, the Wisconsin DNR administers three other major land management programs: Wisconsin State Forests, Wisconsin DNR Land Division, and Wisconsin County Forests (Table 4) (Wisconsin DNR 2009). Through these various programs and DNR divisions, Wisconsin is able to educate companies and individuals about the importance of sustainability. The Wisconsin DNR offers numerous educational and promotional materials to help familiarize the public with forestry certification and is looking for additional ways to market the use of certified wood.

Industry Perspective

According to Terry Mace (2009), head of the Forest Products Utilization and Marketing Program with the Wisconsin DNR, the creation of the state's various certification programs has been the impetus for several Wisconsin sawmills pursuing and obtaining COC certification. In fact, because of the increase in COC certification applications in the state, wood products manufacturers had a 3-month waiting period for auditors to assess their operations in 2009. Through Wisconsin's certification programs, 40 percent of the state's forest land is now FSC certified (state, county, and private). This has increased the supply of certified timber in the state and coupled with the current economic situation, interest in COC certification among manufacturers has increased. Several other states (most notably Indiana) are pursuing or exploring elements of the Wisconsin group forest certification model.

DISCUSSION

The results indicate that members of trade associations are more likely to pursue certification than nonmembers. It is likely that through membership, manufacturers are supplied with industry information and tools that explain certification and the process involved in becoming and maintaining COC certification. Many forest products trade associations have held certification workshops and developed informational packets to aid their members in the certification process. By these means alone, trade associations may provide the catalyst needed for their members to pursue certification.

Although both association members and nonmembers had negative attitudes toward certification, nonmembers' attitudes seem to be more negative than those of association members. Both groups, however, consider themselves environmentally conscious. One reason members of trade associations may be less negative toward certification is because membership in a trade association provides them with certification knowledge that nonmembers may not receive. Most people are vaguely familiar with the concept of forest and COC certification (Mercker and Hodges 2007). Trade associations serve their members by issuing real time information and keeping them up to date on new information and trends in their industry (Suddock 2003).

The complexity of the certification process has often been listed as a major disadvantage of certification. In fact, both association members and nonmembers agreed with the statement "Our company believes that the chain-of-custody certification process is complicated." However, through group certification programs such as the ones AHMI, NWFA, and Wisconsin have, the process of certification becomes easier for landowners and small manufacturing facilities. Not only do members of these group certification programs have additional resources that are unavailable to others, they have the knowledge and experience of fellow group members who have already gone through the certification process.

Certification programs offered through trade associations, environmental organizations, and governmental organizations also address another major issue of forest certification, the costs. According to Butterfield et al. (2005), small landowners and manufacturers can find it difficult to justify the added expense of running certified operations, and the affordability of certification is an issue to them. Group certification programs can eliminate the cost small landowners or manufacturers pay, such as in the case of Wisconsin's MFL program, or they can reduce the amount paid based on economies of scales. AHMI, NWFA, and the State of Wisconsin have been instrumental in increasing the awareness of certification and providing the tools their members need to become certified. Through these programs, the supply of certified hardwood has increased and more companies have become COC certified (Inman 2009, Mace 2009). However, with the change in world markets, hardwood trade associations must do more to change the way they address industry concerns (Barrett 2008).

According to Hardwood Review Weekly, "Trade associations exist to provide benefits and services that either 1) cannot be obtained or provided on an individual corporate level, or 2) could be done more efficiently or effectively with pooled resources and collective representation" (Barrett 2008). Trade associations also can be advocates for their members by educating the public and governmental policymakers on the issues that are most important to their members/industry (Suddock 2003).

Through trade associations, manufacturers are able to form networks that keep them informed of significant industry-related trends and information.

To improve certification among hardwood landowners and manufacturers, it is necessary to understand the uniqueness of the industry. To tailor certification programs so they meet the needs of the hardwood industry, it is important for hardwood products trade associations to be involved in the certification process. These organizations are committed to improving the trade of their members (Barrett 2008). Because the hardwood industry is an important economic component of many states' economies, it is also vital for governmental agencies to become involved with certification. According to Hull and Ashton (2008), government and nongovernmental forestry organizations can support group certification programs by providing financial, technical, and organizational support. Through the cooperative efforts of governmental and non governmental organizations, there is an opportunity to increase the promotion of certification, which could lead to increased pursuance of certification and certified product demand.

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THE ECONOMIC IMPACT OF TIMBER HARVESTING PRACTICES ON NIPF PROPERTIES IN WEST VIRGINIA

Stuart A. Moss and Eric Heitzman[1]

Abstract.—Post-harvest inventories were performed on 90 timber harvests conducted on nonindustrial private forest (NIPF) properties in West Virginia. Each harvest was evaluated based on a combination of residual stocking level, proportion of the residual stand in acceptable growing stock, and damage to the residual trees. Four post-harvest stands representative of good or poor harvest practices were projected for 20 years into the future using the Forest Vegetation Simulator.

Twenty years after harvest, stands subjected to good harvesting were projected to contain twice the volume of high quality sawtimber and nearly three times the volume in acceptable growing stock sawtimber compared to stands subjected to poor harvesting. Good stands also contained much higher volumes in trees 20 inches diameter at breast height (d.b.h.) and larger and had lower future harvesting costs.

After adjusting stumpage prices to account for differences in harvesting costs, tree quality, and tree size, good harvest practices resulted in 20-year timber values three to five times higher compared to poor harvesting. Despite this, poor harvest practices resulted in real internal rates of return (IRR) of 5 to 7 percent, whereas good harvest practices resulted in real IRRs of 4 to 5 percent.

INTRODUCTION

Poor timber harvesting practices are commonly used throughout the Appalachian hardwood region. Many landowners cut their largest, most valuable trees and leave the less valuable trees after harvest (Fajvan et al. 1998; Luppold and Bumgardner 2009; Nyland 1992, 2001; Pell 1998) A survey of nonindustrial private forest landowners (NIPFs) who harvested timber in West Virginia found that 62 percent of the harvests were conducted using a diameter-limit cut, even though professional foresters were involved with 60 percent of the harvests (McGill et al. 2006). In addition, Moss (2011) found that many harvests described by landowners or loggers as "selection" harvests were actually high-grades, and concluded that silvicultural harvesting practices are used on only a small fraction of timber harvests on NIPF properties in West Virginia.

An important factor contributing to the prevalence of diameter-limit harvests and high-grading is the considerable short-term economic benefit that accrues to both the landowner and timber buyer who engage in these practices. What is less well understood are the longer term economic impacts of various harvesting practices. This study provides a 20-year economic evaluation of good and poor harvesting practices that were employed on nonindustrial, private forest land in West Virginia during 2005 to 2007.

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STUDY AREA

This study was conducted on 90 forested sites distributed throughout West Virginia. All sites were owned by nonindustrial, private, forest landowners and had been subjected to partial timber harvesting between January 2005 and June 2007.

METHODS

Field Measurements

Ninety recently harvested NIPF properties in West Virginia were inventoried in 2007 to measure various harvest attributes (e.g., percentage of basal area and value harvested) and residual stand characteristics (e.g., percentage of residual basal area in acceptable growing stock). Each harvest was given an overall evaluation based on three residual stand attributes: (1) stocking level, (2) percent of basal area in acceptable growing stock, and (3) percent of basal area damaged during logging. Using these criteria, we rated each harvest as good, fair, or poor (Moss 2011).

Residual stand data collected during the field investigations were used to project future stand attributes using the U.S. Forest Service's Forest Vegetation Simulator (FVS) Northeast Variant (Dixon 2003). Residual stands from four properties were selected for this analysis: two properties representative of good harvest practices and two properties representative of poor harvest practices. Table 1 lists the important residual stand attributes of these four stands, relative to the average values for all residual stands resulting from good and poor harvest practices investigated by Moss (2011).

Growth Projections

Residual stand data entered into FVS included: diameter at breast height (d.b.h.), species, tree quality, and damage severity. The impact of damage to the residual trees was included in the model as adjustments to future merchantable volume or mortality. Trees with moderate bole damage (100 - 500 in^2 of exposed wood) were assumed to suffer a 10 percent loss in merchantable volume by the end of the projection period (20 years), while trees with severe bole (> 500 $in^{2.}$ of exposed wood) were assumed to suffer a 15 percent loss in merchantable volume by the end of the projection period. Trees with slight bole damage (< 100 in^2 of exposed wood) were assumed to suffer no loss in merchantable volume. Trees with severe crown damage (more than 50 percent of crown removed) and trees with a broken main stem pushed entirely over were assumed to have died during the

Table 1.—Percentage of basal area in acceptable growing stock (AGS), percentage of basal area damaged during logging, and percent stocking level for residual stands subjected to good (G1 and G2) and poor (P1 and P2) harvest practices and average values NIPF harvests in West Virginia rated as "good" or "poor" (from Moss 2011)

Stand	Percent AGS	Percent damaged	Stocking percent
G1	73	4	60
G2	71	2	60
Avg. for 8 "good" stands	70	6	58
P1	46	15	40
P2	50	17	40
Avg. for 38 "poor" stands	49	13	37

projection. These assumptions are consistent with research on the impacts of logging damage to hardwood stands (Lamson and Smith 1988, Lamson et al. 1985, Ohman 1970, Smith et al. 1994).

There were significant differences in the proportion of residual basal area in dominant/codominant trees between tracts subjected to good and poor harvest practices (Moss 2011). Research has shown that crown class is often the single best predictor of future diameter growth in hardwoods, particularly for the more shade-intolerant species, but also for certain shade-tolerant species subject to release (Nyland 2006, Trimble 1969). Low-vigor trees in intermediate and suppressed crown classes often grow slower and are more apt to die (Marquis and Ernst 1991). Thus, tracts subjected to good harvest practices might experience faster growth rates after harvest than tracts subjected to poor harvest practices, all other factors being equal. Unfortunately, the models in FVS do not incorporate crown class/canopy position into the calculation of diameter growth. Therefore, no attempt was made to adjust growth rates based on this attribute. However, the financial analyses of harvesting practices presented in this paper include an adjustment for possible higher growth rates on good tracts.

Stand projections were made for 20 years into the future. This time period was selected because it represents a reasonable timeframe during which re-entry into the stand for future harvesting might occur. Merchantable sawtimber board-foot volume (International 1/4-inch scale) was calculated by species, tree quality, and d.b.h. class.

Determination of Stumpage Prices— Adjustments for Tree Quality and Diameter

Stumpage prices for hardwood sawtimber reflect the expected revenue from the sale of hardwood lumber minus mill production costs, profit, and expenses related to the procurement, harvesting, and transportation of saw logs to the mill. To estimate the value per board foot of lumber expected to be sawn from a log, it is necessary to determine the species, quality, and size of the log.

Luppold et al. (1998) concluded that there is a strong correlation between lumber and stumpage prices over the long term, even though there is weak correlation over the short term. Our study assumed that lumber and stumpage prices are in long-term equilibrium and, as a consequence, lumber prices can be used to derive appropriate stumpage prices.

Hardwood lumber yield data, by species, tree grade, and tree d.b.h. were obtained from Hanks (1976), while Appalachian hardwood lumber prices were obtained from the Hardwood Market Report average prices for June 2007 (Johnson et al. 2007). These data were combined to calculate expected lumber value, per thousand board feet, for each important timber species, by tree diameter and grade. For example, the lumber expected to be produced from a sugar maple tree that is 20 inches d.b.h., contains 32 merchantable feet, and meets Forest Service Grade 2 criteria would have been worth \$116.63 in July 2007. The volume in a 20–inch-d.b.h. two-log tree is 180 board feet, International 1/4-inch scale. Therefore, the expected lumber value from this tree is \$647.95 per thousand board feet (MBF) of tree scale (\$116.63 ÷ 180 * 1000).

These calculations were performed for tree diameters from 12 to 40 inches d.b.h. for each of the three Forest Service tree grades and for the following timber species: red maple, black oak/scarlet oak, sugar maple, black cherry, white oak, yellow-poplar/cucumbertree, northern red oak, and chestnut oak. Because there are no standardized criteria for determining veneer grade, no attempt was made to estimate the potential for future veneer quality for the residual trees. Consequently, there was no need to calculate stumpage prices for veneer-quality trees.

The resulting lumber values per MBF tree scale formed the basis for adjusting stumpage prices to reflect the effects of tree grade and diameter. Prices were obtained from the Appalachian Hardwood Center's Timber Market Report (AHC-TMR) for the second and third quarters of 2007 (Appalachian Hardwood Center 2007). It was assumed that the stumpage prices in the AHC-TMR reflect prices of "average" timber. Although any number of definitions of "average" timber might be appropriate, it was assumed that Grade 2 trees from 16 to 24 inches d.b.h. would constitute "average" timber in most circumstances. For sugar maple, the average lumber value per MBF tree scale for Grade 2 trees from 16 to 24 inches d.b.h. was $676.83/MBF. The statewide average price for sugar maple stumpage reported by the AHC-TMR for the second and third quarters of 2007 was $254.00/MBF. The difference between lumber value per MBF and stumpage price per MBF represents sawmill operating costs, harvest and transportation costs, procurement and transaction costs, market forces arising from localized supply and demand for sugar maple stumpage, and profit for various entities, as well as random variation and market inefficiencies. Collectively, these are referred to as "conversion costs," because they represent all costs associated with converting standing timber into lumber. Subtracting the sugar maple conversion cost of $422.83/MBF from the lumber price per MBF for every combination of tree grade and d.b.h. yields the indicated stumpage prices for various diameters and grades of sugar maple sawtimber trees. For example, subtracting the conversion cost of $422.83/MBF from the expected lumber value for 20-inch grade 2 sugar maple trees ($647.95/MBF) yields an indicated stumpage price of $225.12/MBF for trees of this species, d.b.h., and grade. This process was repeated for the other timber species. Figure 1 summarizes the resulting stumpage prices for sugar maple. Graphs for the other species can be found in Moss (2011).

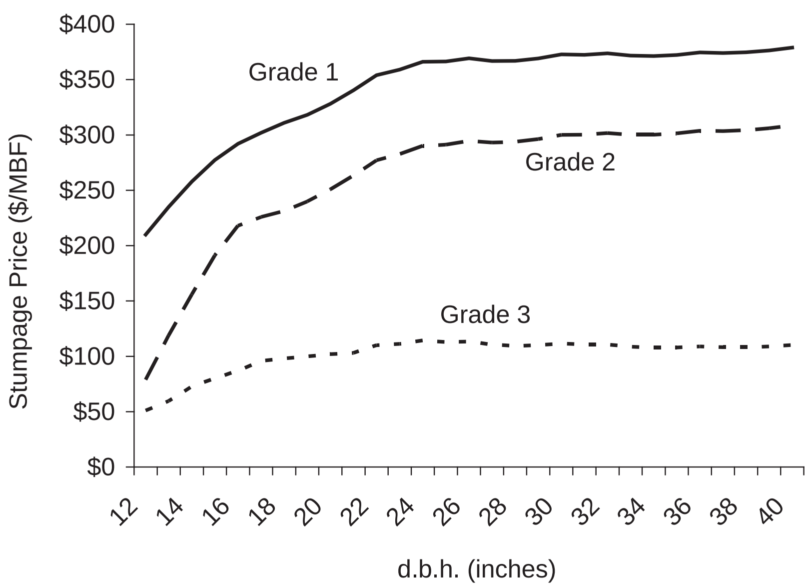

Figure 1.—Estimated stumpage prices for sugar maple trees in West Virginia from 12 to 40 inches d.b.h. and Forest Service tree grades 1, 2, and 3, based on predicted lumber value.

Because the analysis by Hanks (1976) contained only the previously listed eight species, all other species were grouped together as miscellaneous hardwood. To make an adjustment to the miscellaneous hardwood stumpage price from the AHC-TMR, average lumber value by tree grade and d.b.h. for the eight species were used. Although this clearly does not represent the actual lumber values for miscellaneous hardwoods (many of which are low value species), the purpose of calculating lumber value was to adjust the stumpage price reported by the AHC-TMR, and so the method is reasonable.

Determination of Stumpage Prices— Adjustments for Differences in Harvesting Cost

Per unit harvesting costs directly impact stumpage prices and are affected by harvest volume per acre and average tree size (Cubbage et al. 1989, Egan and Baumgras 2003, Li et al. 2006). Twenty years after harvest, projected timber volume per acre and average tree size varied greatly between tracts, as a consequence of the harvest practices initially employed. Stands with significantly different average tree volumes and merchantable trees per acre will incur different harvesting costs because these factors influence felling and skidding efficiency. Therefore, stumpage prices had to be adjusted for possible differences in harvesting costs between tracts.

Harvesting cost was simulated using the Central Appalachian Harvesting Analyzer (CAHA). This model incorporates the important factors that determine harvesting costs for ground-based harvesting systems in the Appalachian Region (Wang and LeDoux 2003, Wang et al. 2004, Wang et al. 2007). The simulated harvesting system used consisted of a single manual feller using a chainsaw, two cable skidders, and a knuckle-boom loader. Site input variables not affected by the harvesting practices being examined (e.g., moving and setup costs, tract acreage, miles of roads constructed, operator efficiency, etc.) were identical for all tracts and were selected by the investigator to represent typical properties in West Virginia. Operating cost variables (depreciation, maintenance and repair expense, labor expense, etc.) were provided by the developers of the computer model and were deemed typical for a harvesting operation in West Virginia. Because the objective was to compare harvesting costs between tracts subjected to various harvest practices, rather than to calculate a highly accurate estimate of harvesting costs, the accuracy of these input variables is unimportant, as long as they are reasonable.

The good and poor harvesting practices examined in this study had significantly different impacts on future per acre timber volumes and average tree diameters. To model these effects, stand tables (trees per acre by d.b.h. class and average board-foot volume per tree by d.b.h. class) were entered into the CAHA model for the initial harvests, as well as 20-year projections for stands G1, G2, P1, and P2. The CAHA model provided default values for felling time per tree. These values reflect the increased time required to harvest larger diameter trees. Skidding efficiency was simulated by assuming three trees are skidded to the landing during each cycle. Therefore, volume per cycle equaled three times the average board-foot volume per tree, with a maximum volume of 600 board feet, to simulate skidder capacity.

Simulated timber harvesting costs using the CAHA are shown in Table 2. The initial (actual) harvests used on the four stands resulted in similar estimated harvesting costs, with an average cost of $101/MBF. This cost was assumed to represent "average" harvesting costs on typical stands. Thus, any

Table 2.—Simulated timber harvesting costs and resulting adjustments to timber stumpage prices ($/MBF) for four NIPF properties in West Virginia subjected to good (G1 and G2) and poor (P1 and P2) harvesting practices over a 20-year projection period; all costs and adjustments are $/MBF

Stand	Scenario	Harvest year	Harvesting cost	Stumpage adjustment
G1	Initial "good" harvest	0	$100	$0
G2	Initial "good" harvest	0	$107	$0
P1	Initial "poor" harvest	0	$98	$0
P2	Initial "poor" harvest	0	$98	$0
G1	Future harvest	20	$99	$0
G2	Future harvest	20	$101	$0
P1	Future harvest	20	$146	- $45
P2	Future harvest	20	$170	- $69

stand with expected harvesting costs of approximately $101/MBF or less would not be subject to any stumpage price adjustment due to excessive harvesting costs. Twenty years after the good harvest, stands G1 and G2 recovered to stand conditions similar to the pre-harvest stands. As a consequence, estimated harvesting costs at Year 20 were similar to the harvesting costs estimated for the initial harvest (i.e., "average" cost) and no adjustment was made to stumpage values at Year 20.

Twenty years after the initial harvest, projected per acre volumes and average tree sizes on stands P1 and P2 were still much less than what was initially harvested, resulting in harvesting costs roughly 50 percent higher than "average" cost. As a result, per acre timber values for these tracts were reduced by $45/MBF and $69/MBF, respectively, at Year 20.

Quality and diameter-specific stumpage prices were applied to the sawtimber volumes harvested from each tract and future sawtimber volumes were projected using FVS. Because the quality of the initial harvested trees was unknown, all harvested trees were assumed to be grade 2. This produced a less precise estimate of the true value of timber that was harvested, but was unavoidable. Unless there were significant differences in the quality of timber harvested on the stands subjected to good and poor harvest practices, the effect on the comparative financial analysis of harvesting practices should be relatively small.

The resulting per acre timber values were then adjusted for above-average harvesting costs, when appropriate, as indicated in Table 1. The resulting net per acre timber values were used in all present value calculations for the financial analyses. Stumpage prices used to calculate future timber values were not adjusted for expected future inflation, and thus represent "real" 2007 prices and assume no real stumpage price appreciation over the 20-year projection period.

Selection of Discount Rates

One of the most troublesome aspects of financial analyses is the selection of an appropriate discount rate to apply to future cash flows. The purpose of a discount rate is to reduce (discount) future revenues/benefits to account for: (1) delayed consumption (all else being equal, we would rather enjoy benefits now rather than later) and (2) risk (future revenues/benefits are not certain). Time preference for consumption (placing a discounted value on future benefits because we must wait to receive them) varies among individuals and is affected by many factors. Likewise, individuals have varying levels of risk tolerance/aversion and, therefore, require differing levels of compensation as reward for assuming risk. To further complicate matters, risk is often difficult to quantify, so individuals may have varying perceptions of the risk involved in a particular investment/activity.

Given that NIPF owners are a numerous and diverse group, it is difficult to derive a single discount rate, or even a relatively narrow range of discount rates, that might be appropriate for analyzing forestry practices on NIPF land. To address this issue, financial analyses for this study were done using a range of real (inflation-adjusted) discount rates from 1.0 to 10.0 percent. The resulting "present value profiles" graphically illustrate present values for various options/scenarios for the range of discount rates analyzed. This allows the reader to ascertain the range of discount rates under which one scenario would be financially superior to another. Readers are free to select the discount rate they feel is most appropriate and draw their own conclusions about the attractiveness of each option/scenario, rather than being presented with an analysis showing which option is superior under a single, predetermined discount rate assumption. In addition, internal rate of return (IRR) can be derived from net present value profiles, because net present value will equal $0 at the discount rate that is equal to the IRR.

RESULTS

After 20 years, projected sawtimber volumes on the good stands are approximately twice as great as on the poor stands (Table 3). As a result of larger tree sizes, better tree quality, and lower harvesting costs, projected values on the good stands are approximately three times greater than values on the poor stands. The volume of acceptable growing-stock trees 20 inches d.b.h. and greater is more than six times as great in the good stands compared to the poor stands.

Because there are significant differences in initial timber value on the various stands (due to differing volumes, species composition, and timber quality), there is limited insight to be gained by directly comparing present values of the different stands. To adjust for differences in initial timber value, net present value (NPV) was calculated for each tract. In this method, initial timber value is treated as an opportunity cost and is subtracted from harvest income and discounted future timber value. This is financially appropriate, because partial harvesting in Year 0 followed by a second harvest (or disposal of the property) in Year 20 implies forgoing the income that could be received from liquidating the timber (clearcut harvest or property sale) in Year 0. Essentially, calculating NPV in this manner determines the long-term financial gain (or loss) realized by the landowner as a result of various harvesting techniques (in our case good or poor practices), assuming the initial timber value represents an investment by the landowner.

Table 3.—Initial stand, harvested, and projected future timber volumes and value for four NIPF properties in West Virginia subjected to good (G1 and G2) and poor (P1 and P2) harvesting practices (volumes in board feet per acre, International ¼-inch scale; values in dollars per acre; AGS20 = board-foot volume in acceptable growing-stock trees 20 inches d.b.h. and greater)

	Preharvest stand		Initial harvest		20-year projection		
Stand	Volume	Value	Volume	Value	Volume	Value	AGS20
G1	13,887	$1,831	8,459	$1,274	9,399	$1,192	3,218
G2	11,039	$1,545	5,255	$873	9,996	$1,410	3,486
P1	12,450	$1,892	10,174	$1,730	4,779	$449	543
P2	11,542	$1,400	10,062	$1,314	4,302	$324	716

Net present value profiles for stands G1, G2, P1, and P2 over a 20-year projection period are presented in Figures 2 and 3. The accelerated growth rate scenario (Fig. 3) assumes that stands subjected to good harvest practices will achieve projected 20-year volumes in only 16 years.

For the 20-year projection period, NPV is greater for the stands subjected to good harvest practices (G1 and G2) compared to the stands subjected to poor harvest practices (P1 and P2) for all discount rates less than about 3 percent. Net present value falls more steeply with increasing discount rate for the two good stands compared to the two poor stands, because a larger proportion of total value is realized at the end of the projection period and is therefore subject to discounting. Trends for the two good stands are similar, as are the trends for the two poor stands, suggesting that these trends can be generalized for all stands in this study subjected to good and poor harvest practices.

At discount rates below 4 percent, NPVs of the good stands are positive, indicating that landowners are better off financially by performing a silvicultural harvest versus liquidating their forest. This indicates a real internal rate of return of approximately 4 percent for landowners engaging in silvicultural harvests.

Engaging in poor harvest practices yielded financial gains for landowners at all discount rates below 5 percent, as indicated by the positive NPVs (Fig. 2). The real internal rates of return for the two poor stands are 5 percent and 7 percent.

Assuming accelerated growth for the stands subjected to good harvest practices, NPV is greater for the good stands (G1 and G2) compared to the poor stands (P1 and P2) for all discount rates less than approximately 4.5 percent (Fig. 3). At discount rates below 5 percent, NPVs of the good stands are positive, indicating that landowners are better off financially by performing a partial harvest using silvicultural guidelines versus liquidating their forest. This indicates a real rate of return of 5 percent for landowners engaging in silvicultural harvests.

DISCUSSION

The analysis of the effects of tree grade and d.b.h. on lumber value and, subsequently, stumpage price, clearly indicated that tree quality and size are important considerations when determining standing timber value. Good harvest practices yielded greater sawtimber volumes than poor harvest practices 20 years after the initial harvest. However, the effects on timber value were much greater than the effects on sawtimber volume, due to the significant differences in average tree size and timber quality. In addition, future per unit harvesting costs were higher on tracts subjected to poor harvest practices, as a result of the lower felling and skidding efficiencies incurred on tracts with a lower per acre volume and a smaller average tree volume. This further reduced future stumpage values on these tracts.

Despite their negative impacts on sawtimber volume, timber quality, and harvesting cost of the future stand, poor harvest practices were deemed to be financially attractive to landowners. Although good harvest practices yielded 20-year timber values two to five times higher than poor practices, the much higher initial harvest income generated by poor harvesting resulted in higher net present values at all real discount rates greater than about 3 percent. Landowners engaging in poor harvesting were projected to realize real internal rates of return (IRR) of 5 to 7 percent, compared to 4 percent for

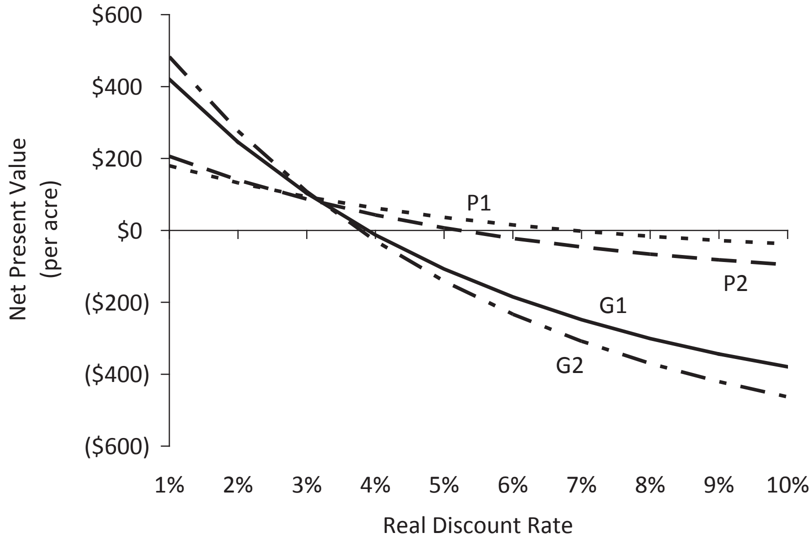

Figure 2.—Net present values for four NIPF properties in West Virginia subjected to good (G1 and G2) and poor (P1 and P2) harvesting practices over a 20-year projection period at real discount rates from 1.0 to 10.0 percent.

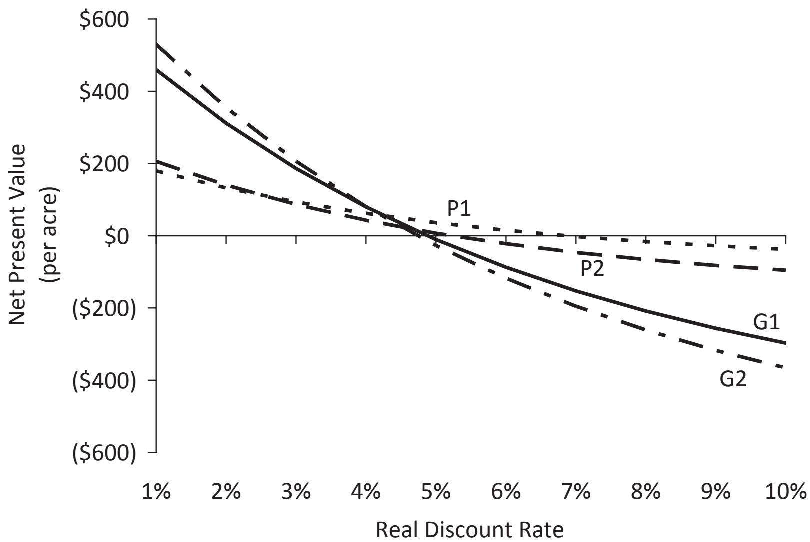

Figure 3.—Net present values for four NIPF properties in West Virginia subjected to good (G1 and G2) and poor (P1 and P2) harvesting practices over a 20-year projection period at real discount rates from 1.0 to 10.0 percent, assuming accelerated growth rates for tracts subjected to good harvesting practices.

landowners who performed good harvests. If good harvest practices result in higher timber growth rates, the real IRR for good harvest practices increases to 5 percent, making them more competitive with the returns from poor harvest practices. These findings are consistent with other research in this area that suggests that silvicultural harvests can yield real returns of 4 to 6 percent (McCauley and Trimble 1972, Reed et al. 1986).

The failure of good harvest practices to outperform poor harvest practices in financial terms, despite being clearly superior from a silvicultural standpoint, is a result of the larger initial income derived from poor harvest practices and the significant discounting of the larger future timber values achieved through good harvest practices. This discounting is accentuated by the relatively long time lapse until subsequent harvest. Timber growth rates in the Appalachian hardwood region will necessitate relatively long-periods between harvests and, subsequently, relatively high discounting of any benefits obtained from silvicultural practices, including harvesting practices.

The applicable discount rate is determined by the market and is not subject to manipulation or management. Simply put, we must accept the discount rates deemed appropriate by the market. If they are high, we must accept the consequence that future values will be highly discounted. If future values occur well into the future, as is the case with forestry, these values may be discounted so highly that they become almost irrelevant.

To overcome the limitations imposed by relatively long discounting periods (i.e., 10 to 15 years between harvests) and relatively high discount rates (i.e., greater than 3 percent real), it is necessary to realize significant premiums for higher quality and/or larger diameter timber to justify silvicultural harvesting from a financial standpoint. Although this study used stumpage prices that accounted for timber quality and tree diameter (as well as harvesting cost), these premiums were generally insufficient to compensate for discounting (a function of time and discount rate) unless fairly low discount rates were assumed. It is impossible to determine if these adjustments reflect premiums actually paid by the market, because actual stumpage price data are relatively scarce and generally reported only by species, with no adjustments for grade or d.b.h. If actual premiums for quality and tree size are larger than those assumed in this study, that would improve the financial performance of good harvest practices relative to poor harvesting practices.

However, it is uncertain whether landowners actually realize any premium for timber that is of superior quality or larger than average diameter. To realize premiums for timber quality and size, if they even exist, sellers must market their timber to maximize competition between buyers. In this situation, savvy buyers will recognize the higher value present in quality timber stands and will offer higher prices accordingly, to outcompete other buyers. Without this, it is unlikely that sellers realize any premium for quality timber. For good harvest practices to financially benefit landowners, there must be a sufficiently large premium for quality timber and landowners must sell their timber to captures this premium. Both requirements are paramount. Unfortunately, there is scant evidence that either of these conditions is prevalent in the state, especially the latter. McGill et al. (2006) found that many West Virginia landowners sold timber through negotiation or on a percentage-of-receipts basis and only about one-third retained the services of a consulting forest to assist with marketing their timber. For landowners with a tendency to negotiate directly with buyers, there is little incentive to practice good harvesting, because they are unlikely to capture the future financial gains of doing so. This provides further incentive to engage in high-grading.

Another issue relevant to the comparison of good and poor harvest practices is their effect on length of time between harvests. In our study, tracts subjected to good harvest practices could reasonably support a subsequent harvest after just 10 years (Moss 2011). It is highly questionable whether tracts subjected to poor harvest practices could support another commercial harvest in 10 years, due to low per acre volumes, a high proportion of less valuable species, and the relative scarcity of quality timber, particularly timber in the larger diameter classes. These factors, coupled with the higher per unit harvesting costs on these tracts, result in stands that are financially unattractive to buyers. Even after 20 years, there is a question as to whether these tracts could attract the interest of buyers in a normal market, unless the timber is sold at a discount. This is consistent with the conclusions drawn by Reed et al. (1986).

The inability to conduct future harvests within 10 to 20 years exposes these tracts to increased market risk (Ferguson 2006). Timber prices exhibit significant fluctuation, both in the long term and the short term, and the sellers' ability to respond to these fluctuations is critical to maximizing financial returns. Landowners in our study who engaged in good harvest practices (e.g., owners of stands G1 and G2) retained the ability to respond to favorable markets in 10 years by conducting another sale. Landowners who engaged in poor harvest practices (e.g., owners of stands P1 and P2) forfeited this option by harvesting their timber so intensely with the initial harvest. They have, in effect, put all their eggs in one basket – the initial harvest. This behavior incurs additional risk. Although these landowners are expected to realize higher rates of return than landowners who engaged in good harvesting practices, they should demand higher returns as a result of their greater exposure to market risk. Therefore, it is inappropriate to conclude that poor harvest practices are financially superior to good harvest practices simply because they resulted in higher rates of return. Unfortunately, because most NIPFs lack the knowledge or skills to adequately access market risk, let alone access how their harvesting decisions affect their exposure to such risk, it is unlikely that they can properly evaluate the financial consequences of their actions. In the absence of knowledge about relative risks, investors universally choose the option with the highest expected return. For landowners in Appalachia, this generally means engaging in poor harvest practices.

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ENGAGING LANDOWNERS EFFECTIVELY: CREATING A CALL BEFORE YOU CUT CAMPAIGN IN THE CENTRAL HARDWOODS REGION

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Abstract.—Social marketing tools and approaches were used to develop a Call Before You Cut campaign for six states in the Central Hardwoods Region (Illinois, Indiana, Iowa, Missouri, Ohio, West Virginia). The campaign was developed from research on landowner values, objectives, and behavior, based on National Woodland Owner Survey data and landowner focus groups, and discussions with natural resource professionals in the region. The result was a strategically focused set of publicity materials, a Web site, and an informational packet common to all six states and designed to attract the attention of and be useful to the landowners most likely to cut trees without professional advice.

INTRODUCTION

Decisions made by millions of family forest owners are the key to the sustainability of U.S. forests. Collectively, their actions enhance or degrade the landscape; how they manage their forests and whether they convert them to other uses is of significant public interest. Only 3 percent of private woodland owners have a written forest management plan, and 78 percent of them fail to seek the advice of forestry professionals when conducting timber harvests (Butler and Leatherberry 2004). Reaching these unengaged woodland owners, especially when they are contemplating a timber harvest, is critical to ensuring that forest resources are sustainably managed. Woodland owners who make well-informed decisions and who are actively engaged in caring for their land help ensure that healthy forests persist for many generations and that forestry remains relevant.

The Sustaining Family Forests Initiative (SFFI)[2], using a social marketing approach, has developed a practical set of tools to help conservation and forestry professionals reach more landowners with effective stewardship messages and to develop programs that better serve the needs and values of the landowners. These tools were developed from survey and focus group research on landowner values, objectives, and behavior, as well as from interviews with natural resource professionals in forestry and conservation throughout the country (SFFI 2009).

Creating data and information is one thing, but putting it to practical use is quite another challenge. After completing a research project to develop more expansive information about family forest owners (Butler et al. 2007), SFFI had a wealth of new information about landowners, particularly

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[2]SFFI is an ad hoc collaboration of universities, government agencies, conservation organizations, forest industry companies, certification systems, and landowner groups, organized to gain comprehensive knowledge about family forest owners in the United States. More information is available at www.sustainingfamilyforests.org.

how they cluster with respect to values and attitudes toward their land. The next logical question was: How could natural resource professionals use this information to improve their landowner outreach programs? The Central Hardwoods Call Before You Cut (CBYC) campaign was initiated to test the use of landowner data and application of social marketing principles to develop a program that would change landowner behavior – in this case, getting professional help before harvesting their trees. A campaign strategy and outreach materials were developed for six states (Illinois, Indiana, Iowa, Missouri, Ohio, West Virginia), in a collaborative process with the state forestry agencies, university extension, the U.S. Forest Service, and the Sustaining Family Forests Initiative.

PILOT PROJECT AND STUDY AREA

To test how to apply our social marketing research findings in an actual outreach project, we chose the six-state CBYC campaign in the Central Hardwoods Region as the pilot project. This region is suffering from widespread destructive harvesting practices that degrade the value of the family's assets and the region's forests. The six states received a grant to develop a common outreach campaign, intended to provide the landowner with a whole suite of information on sustainable harvests as well as practical help such as lists of accredited foresters and master loggers.

More than 70 million acres of complex Central Hardwoods forests in the Midwest and Lake States provide abundant supplies of some of the world's most valuable hardwood timber. These forests help clean rural and urban waterways, provide critical wildlife habitat, and bring great beauty to the region. Seventy-two percent of the woodland acreage in the six states participating in CBYC is classified as family forest (Butler 2008). Many woodlands are threatened by land use change, climate change, and poor management decisions. One of the greatest impacts on the health of these woodlands, and the subsequent protection of water supplies and wildlife diversity, often lies with decisions made about harvesting timber by these family forest owners.

When questioned, most woodland owners indicate they have no intention of harvesting timber (Butler 2008). Nevertheless, when faced with a financial crisis or approached by a logger, woodland owners in significant numbers opt to harvest their woods. In the six CBYC states, only 13 percent of woodland owners indicate that harvesting timber is a priority, yet 53 percent have harvested trees (37% for commercial purposes) during their tenure as woodland owners (Fig. 1) (Butler et al. 2011). Uninformed decisions, lack of planning, and ignorance of what constitutes a good harvest can be devastating to forest ecosystems and a landowners' finances. State forestry officials frequently receive calls from landowners who regret signing vague contracts that offered little financial or forest protections.

CHOOSING A TARGET AUDIENCE

Our approach was to apply targeted marketing to solve natural resource problems that are behavioral (social) in nature. What we are calling "targeted marketing" is basically the same as the more commonly used term "social marketing," but we believe it is clearer in this context. In its broadest sense, marketing means designing programs to persuade people to take a desired action, whether enrolling in a cost share program, planting more trees, or getting a management plan. Targeted marketing means designing communications to bring about a specific behavior change in a selected group of people. Otherwise put, targeted marketing differs from a broad-brush approach in that it

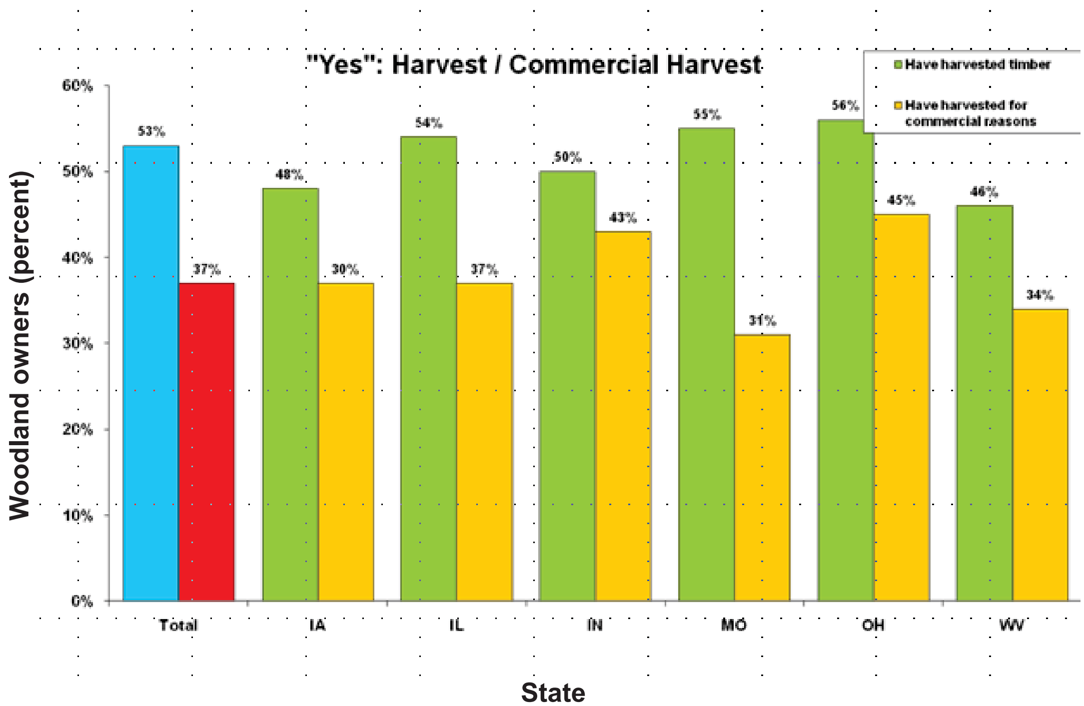

Figure 1.—Percentage of woodland owners who indicated they have harvested timber (left side of paired bars) and have harvested timber for commercial reasons (right side of paired bars). “Total” bars show average for all six CBYC states, followed by paired bars for each state.

seeks to reach subsets or groups of people with messages that are most likely to appeal to them based on an understanding of their values, preferences, and other characteristics (Bloom and Novelli 1981, Donovan and Henley 2003).

We drew on data from the SFFI research for the six states to develop a profile of landowners there. These data included basic demographics, attitudes toward their land, engagement with their land, and future plans for their land. A 1-day workshop was held with representatives from all six states to introduce them to the benefits of targeted marketing, review the data for their states, and decide which landowner attitudinal group to target for the CBYC campaign (Fig. 2) (Butler et al. 2007).

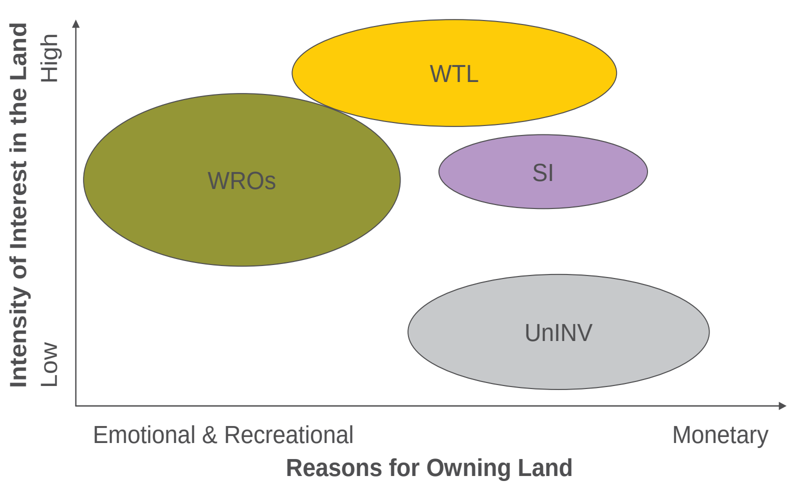

Figure 2.—The four attitudinal segments identified in the SFFI analysis for the six CBYC states showing where they fall on the scales of interest and reasons for owning. The sizes of the ellipses indicate the relative size of each group for the six states combined. WTL, WROs, SI, and UnINV refer to Working the Land, Woodland Retreat Owners, Supplemental Income, and Uninvolved, respectively.

The consensus was to target the segment referred to as Working the Land (WTL) owners. Data about the four attitudinal groups (WTL, Woodland Retreat Owners, Supplemental Income, Uninvolved) in the six states show that WTL owners have the highest intensity of interest in the land, and their appreciation of their woods is based on its commercial and recreational/emotional value. Twenty-six percent of all landowners who own between 10 and 1,000 acres in the six states fall into this segment, and they account for 29 percent of the land in this category held by family forest owners (Fig. 2).

Compared to the other large segment of landowners in the six-state region, Woodland Retreat (WR) owners, SFFI data show that:

- WTL owners are much more likely to cut trees (for any reason), and they are much more likely to harvest trees for timber (40% vs. 25%). Thus, the message of this campaign—call for information before you cut—is more relevant to this group.
- WTL owners are also more likely to believe in managing their woods proactively. They are much more likely to believe that trees, like crops, need to be tended while they are young and then harvested when they reach maturity. Nonetheless, only 16 percent have sought professional advice about managing their woodland.
- Because WTL owners see their woods as a valuable financial asset, they are more likely to be persuaded to invest more time and attention in managing their woods. They may also be more likely to see consultant forester fees as an investment in future returns, once they understand what a forester can do for them.
- On average, WTL owners have slightly larger land holdings, which means that outreach activities and land management services can be delivered more efficiently.

PROFILING THE TARGET AUDIENCE

To learn more about the target audience, we conducted six focus groups with WTL owners, two each in Ohio, Iowa, and Indiana. The main purpose was to probe their willingness to ask for advice about cutting trees and learn how best to reach them with compelling messages. Test messages were developed by social marketing professionals at the Center for Nonprofit Strategies and reviewed and modified by the project team. Landowners were chosen at random from property tax records and called by professional recruiters. A recruiting screener was used to identify people who own at least 10 acres of wooded land and self-identified as making or sharing decisions about their land. A question about reasons for owning land was used to determine which attitudinal group they fell into. There were 8 to10 participants in each group.

The focus groups were led by professional facilitators, using a topic guide. They were first asked to introduce themselves and talk about what they liked and disliked about owning woodland. The participants were then shown a series of messages, asked to rate them on a scale of 1 to 7, cross out any words they disliked or found confusing, and circle words they liked. The messages were crafted to test the appeal of different themes: traditional values, getting a fair deal, doing right by the land and for the family, harvesting at the right time, wildlife, and resistance to asking for advice. Other topics discussed were reasons for consulting a forestry expert, possible CBYC campaign products, inclination to call a toll-free number or go to a Web site when considering a harvest, and preferred sources and channels of information.

In general, messages that appealed to WTL owners focused on healthy woods, financial benefits, recreation, value for timber, and harvests that leave the land in good shape. These owners see their woods as among their main assets and want to get the best from their land. Compared to other groups, WTL owners use the land more intensively—for timber, firewood, nontimber forest products, hunting and fishing, and other recreation. Their most distinguishing characteristic is that they cite a mix of recreational and commercial uses for their land, and they value both equally. While their approach is pragmatic, their interest in their woods is not merely utilitarian. Land ownership is a source of pride and security for WTLs. They are deeply attached to their land and, of all the segments, least likely to say they plan to sell their land in the next 5 years. Many have farming roots and see land as the only true and real wealth that outlasts all other assets. True to a traditional farming philosophy, they also believe that land should be used respectfully (i.e., sustainably) and that it is their duty as landowners to ensure that the land remains healthy for future generations to enjoy and use. Thus, they try to use the land to the fullest while maintaining its health and productivity for the future.

In this region, most WTL owners see state service foresters as the most reliable source of information on how to keep their woods healthy and safe from diseases, pests, and invasive species. Not many landowners have used the services of consulting foresters. They view loggers with a healthy skepticism. They realize that unscrupulous or untrained loggers can harm them in many ways—e.g., by underpaying for their timber, by cutting trees before the time is right, or by damaging the woods while logging. They believe that the only way to get a good logging operation is to hire a trustworthy logger and monitor the logging closely.

DEVELOPING A CAMPAIGN

Results of the focus groups were synthesized with SFFI landowner data to create draft campaign strategy recommendations that were reviewed and discussed at a second 1-day workshop with project leaders and communication specialists from the six states. The result was a campaign strategy and briefing document developed by the SFFI team for the states to use in implementing the campaign.

Campaign Goals and Desired Landowner Behaviors

The broad goal of the Call Before You Cut campaign (CBYC) is to protect the interests of landowners and improve the quality of logging to sustain forests and prevent environmental damage. This goal can be achieved if (1) landowners are better informed about the silvicultural, financial, and legal elements of planning and implementing a harvest; and (2) more landowners use the services of a professional forester to plan and manage their harvest.

Because most woodland owners harvest trees only once or twice in their lifetime, it is crucial they get the relevant information about harvesting when they need it. Therefore, the campaign's first objective was to publicize the availability of campaign materials and to position the CBYC campaign as the most comprehensive and reliable source of information and resources to help woodland owners make informed decisions about harvesting trees from their woods. This publicity was aimed at getting landowners to call a toll-free number or visit the CBYC Web site for help and guidance when they are thinking of cutting their trees.

The campaign also developed materials that would provide landowners with appropriate information and guidance to plan their harvest better and choose appropriate service providers. Among other things, these materials explained the benefits of working with a forester.

Tailoring Messages to the Target Audience's Motives

The main motivation of WTL owners in harvesting timber is to maximize the long-term value of their woodland, where the term "value" is used holistically to include financial, recreational, and emotional benefits of owning woods. The CBYC materials were therefore presented as tools to help landowners harvest trees in a way that maximizes the long-term value they get from their woods.

In keeping with the strong independent streak in WTL owners, and their tendency to trust experience and judgment (particularly their own) over expert advice, the campaign focused on informing woodland owners about how to plan and manage a good harvest**.** The services of a professional forester were positioned as a resource to help landowners implement their plans and accomplish their objectives for the harvest.

In a nutshell, the theme for the campaign was: **If you're thinking of harvesting your trees, call the CBYC number to get all the information you need and understand what resources are available to you. This will help you get the best value from your woods, now and in the future.**

Under this theme, campaign materials focused on four key messages:

1) **Do Right by Yourself and Your Family**. You can cut a tree only once. So plan your harvests carefully to get the best value from your woodland.
2) **Enjoy your Woods.** Good decisions at harvest time will keep your woods healthy and productive for you and your family to enjoy. You do not have to choose between harvesting timber and enjoying your woods.
3) **Do Right by the Land**. Your woods are valuable; take care of them and they will serve you and your family well for many years to come.
4) **Be Woodswise.** The CBYC can provide you with all the information you need to make good decisions for your land and your family, and it connects you with services and resources in your community.

Overall, the CBYC campaign was clearly designed to serve the interests of landowners—not foresters, the timber industry, or other professionals. We realized that it would lose all credibility if it was seen as a mouthpiece for promoting the services of consulting foresters or other providers. We also took care not to be seen as reflecting an environmental (greenie) or commercial agenda, and we were neutral with regard to hunting. As a group, WTL owners are divided on these issues, any of which can be a hot button that leads to impassioned debates. Finally, we were clear that the CBYC is about helping landowners harvest their trees to get better long-term value from their land. Campaign materials focused on that—they did not try to push lessons in forest management, development of written plans, or enrollment in government programs.

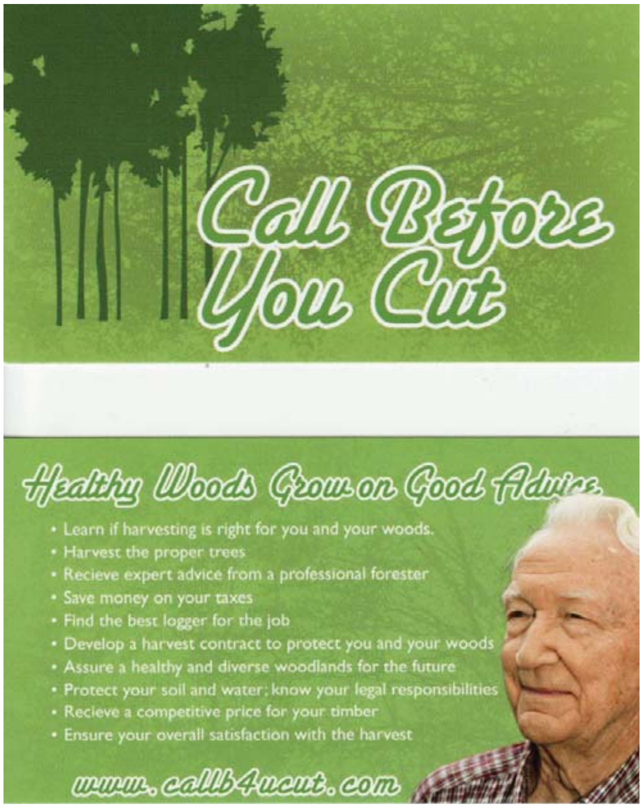

Figure 3.—Business cards developed for use in all six CBYC participating states.

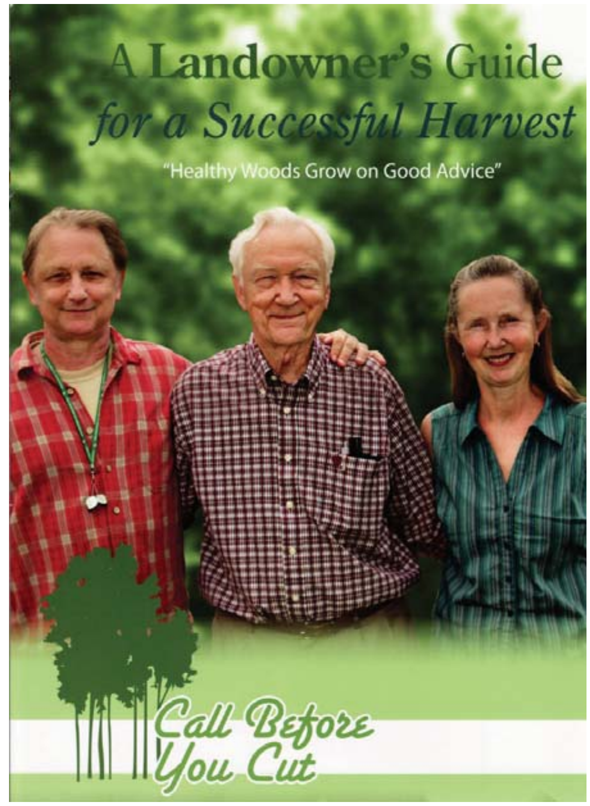

Figure 4.—Standardized folder to be used in all participating states in the CBYC campaign. Tabbed inserts were customized for each state.

DESIGNING CAMPAIGN MATERIALS

Materials were developed to create awareness of the CBYC campaign (Fig. 3, business cards, posters and billboards) and items to aid in implementing the campaign (folders for dissemination of information and Web pages for use in participating states). All materials were designed as templates that could be customized for use in each of the six participating states. For example, tri-fold folders were developed (Fig. 4) with a generic message that was valid in all participating CBYC states, but they were designed to accept inserts that could be customized to the needs of each state. A common launch Web site was developed to allow for the use of a single, simple URL for all participating CBYC states, and a Web site template was developed to provide uniformity among CBYC Web sites (Fig. 5). The language, look, and feel of materials were also tailored to the characteristics of the target audience. Because WTL landowners are independent and resistant to taking direction, the tone of this packet was informational—i.e., CBYC is providing landowners with good information to help them make decisions. Rather than make forceful recommendations (which this target audience is likely to resist), we offered ideas and suggestions (along with a rationale).

The language of the materials was also simple and folksy, peer-to-peer rather than expert-to-novice. We focused on giving landowners practical advice rather than theoretical information and used anecdotes, peer testimonials, analogies, and parables to get our point across. Because WTL owners generally tend to be well informed and seek out different points of view, we carefully acknowledged controversial or different points of view and addressed them directly. Also, WTL owners are typically not enthusiastic readers; therefore, we minimized the text and used bullets and other means to simplify and organize it.

Figure 5.—Web pages for CBYC campaign. Left: Launch site for all participating CBYC states (http:callb4ucut.com). Right: Ohio's CBYC Web page (http://callb4ucut.com/Ohio/tabid/107/Default.aspx).

EVALUATION

Evaluation is a key, although often overlooked, part of social marketing. It is imperative to assess what is working and what is not in order to improve the communications campaign. The evaluation should be tailored to the specific project, include both short-term and long-term measurements, and be a continuous process.

For the CBYC campaign, the immediate metrics will be simply the volumes of traffic on the Web site and the toll-free number. From June 2010 through May 2011, the Ohio CBYC campaign received about 1,650 requests; more than 95 percent of those requests were by email via the Ohio CBYC Web page (Ohio Division of Forestry 2008). We will also keep track of when specific campaign elements, e.g., newspaper articles, are run to see how this impacts these volumes. In the longer term, we will use a short survey, such as a postcard, to contact those who have contacted CBYC to evaluate how they heard of it and how useful were the materials they received. Although not currently planned, more in-depth work could be done with the people contacted to better understand these topics and a broader survey could be done to understand awareness of CBYC by those who had not contacted the program.

ACKNOWLEDGMENTS

The authors thank Andy Ware, previous Assistant Chief of the Ohio Division of Forestry, for his vision for and leadership of the Call Before You Cut campaign, and the participating state forestry divisions from Illinois, Indiana, Iowa, Missouri, Ohio, and West Virginia for their cooperation. The Call Before You Cut campaign and this research, in part, were supported by the U. S. Forest Service, Northeastern Area State and Private Forestry project numbers 08-DG-1142004-213 and 09-DG-11420004-201with matching funds from the Sustaining Family Forest Initiative (SFFI).

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FOREST HEALTH

BIOTIC AGENTS RESPONSIBLE FOR RAPID CROWN DECLINE AND MORTALITY OF HICKORY IN NORTHEASTERN AND NORTH CENTRAL USA

Jennifer Juzwik, Ji-Hyun Park, Mark T. Banik, and Linda Haugen[1]

Abstract.—Severe decline and mortality of hickory (*Carya* spp.) occur periodically in the eastern United States. Recently, rapidly declining crowns followed by tree mortality were found to be the predominant symptoms based on a 2 year survey in six north central and northeastern states. Stems of actively declining bitternut hickory (*Carya cordiformis*) exhibited numerous cankers and evidence of hickory bark beetle (*Scolytus quadrispinosus*) (Hbb) colonization. Main stems of three affected trees (40 to 80 percent crown decline) had 178 to 1,448 bark beetle attacks. *Ceratocystis smalleyi*-caused cankers and xylem lesions were associated with 13 to 37 percent of these attacks. The fungus was commonly isolated from adult Hbb attacking bitternut hickory in late summer, but not from Hbb emerged from declining trees in early summer. Fifty *C. smalleyi* inoculations (2 to 4 m stem height) of eight bitternut hickory (13 to 28 cm diameter at breast height [d.b.h.]) resulted in reduced sap flow rates (35 to 86 percent) 12 to 14 months after treatment compared to nine controls. More xylem vessels were occluded by tyloses in inoculated trees compared to controls. These results suggest that multiple cankers and xylem dysfunction caused by *C. smalleyi* are likely major contributors to crown decline. The disease is apparently a result of the synergistic interaction of Hbb and the pathogen.

INTRODUCTION

Hickory decline, particularly of bitternut hickory (*Carya cordiformis*) and shagbark hickory (*C. ovata*), to a lesser extent, has recently been noted in Iowa (Johnson et al. 2005), in Missouri, Maryland, New York, Pennsylvania, and West Virginia by Forest Health Monitoring (Steinman 2004), and in Wisconsin (Wisconsin DNR 2005). A Forest Service-led project was initiated in 2007 with funding from the Forest Health Evaluation Monitoring Program to elucidate cause(s) of the widespread problem (U.S. Forest Service 2011). Based on a 2007-2008 field survey conducted in six states as part of the project, the most common hickory health problem observed in affected stands involved rapidly declining crowns of smooth-bark hickories (bitternut and pignut [*C. glabra*], in particular) over 1 to 2 years followed by tree death (Juzwik et al. 2009).

Historically, episodes of hickory mortality have occurred periodically since the early part of the 20th century. At that time, serious mortality of the species was documented in much of their natural range from Wisconsin to Vermont and south to central Georgia (Hopkins 1912). Within the first decade of that century, thousands of hickories died in central New York State alone (New York State Museum 1910). Subsequent periodic episodes were observed and reported through the rest of the century (U.S. Forest Service 1985). In Wisconsin, for example, episodes of hickory decline or dieback have been reported in the late 1960s, late 1980s, and early 2000s (U.S. Forest Service 1994, Wisconsin DNR 2005).

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Widespread mortality of hickory has historically been attributed to outbreaks of the hickory bark beetle (*Scolytus quadrispinosus*) during extended periods of drought (U.S. Forest Service 1985). The insect is considered the most important pest of hickory species (Solomon and Payne 1986). In 1994, a newly discovered fungus was reported in discolored wood and sunken bark cankers associated with beetle attacks (U.S. Forest Service 1994). This fungus, *Ceratocystis smalleyi,* and a related species, *C. caryae*, were recently described (Johnson et al. 2005). Both species were pathogenic on 2-year-old *Carya* spp. in greenhouse studies. The researchers suggested that *C. smalleyi* might play a significant role in hickory mortality. Subsequent field inoculations on pole-timber sized bitternut hickory in Iowa and Minnesota documented the ability of *C. smalleyi* to cause large bark cankers and xylem lesions on the species within 12 to 14 months after inoculation (Park et al. 2010).

Field and laboratory studies were conducted between 2008 and 2011 to investigate the nature of the interaction between the hickory bark beetle and *C. smalleyi* on stems of bitternut hickory with actively declining crowns and to determine the role of *C. smalleyi* in rapid crown decline and mortality in this species. Specific objectives for the fungus–bark beetle studies were to: 1) document the frequencies of occurrence of *C. smalleyi* cankers and hickory bark beetle attacks on bitternut hickory with actively declining crowns, and 2) determine the frequencies of hickory bark beetles carrying propagules of *C. smalleyi* when initially attacking bitternut hickory and when emerging from colonized trees. Specific objectives for the studies focused on the pathogen were to: 1) document sap flow rates in multiple-cankered bitternut hickory versus canker-free trees, 2) explore relationships between sap flow rates and extent of stem cankering as well as induced host responses that are known to reduce xylem water flow, and 3) document extent of pathogen colonization and host response in the xylem of artificially inoculated bitternut hickory. This paper proposes Ceratocystis wilt of hickory caused by an interaction of *C. smalleyi* and the hickory bark beetle as a new disease that is hypotheized to cause crown decline and tree mortality.

STUDY AREAS

In general, forest stands of 4 to 89 ha with different levels of hickory stocking were used for the field studies. Crown decline and mortality of bitternut hickory were common in the stands. The field site in Minnesota (Wabasha County) was in a mixed hardwood stand (4 ha) with pole-timber size (13 to 28 cm d.b.h.) bitternut hickory accounting for 40 percent of the stand. Field studies were conducted at three sites in Wisconsin. The mixed hardwood stand (8 ha) used in Chippewa County, WI, was thinned during winter 2007-2008. In 2009 and 2010, bitternut hickory made up 20 to 25 percent of the stand and was mostly pole-timber size. A privately-owned mixed hardwood stand (32 ha) with 25 percent bitternut hickory in Marathon County, WI, included both pole and sawtimber size (> 28 cm d.b.h.) bitternut hickory. The Shawano County, WI, stand was located on Stockbridge-Munsee Community lands and consisted of 89 ha of mixed hardwoods with 25 percent bitternut hickory, primarily >28 cm d.b.h.

MATERIALS AND METHODS

Debarking Stems of Trees with Declining Crowns

Two bitternut hickory with 40 and 55 percent crown decline in Marathon County and one with 80 percent decline in Chippewa County were felled in June 2009. The main stems of the trees (21 to 23 m tall) were cut into approximately one meter long sections, wrapped in insect screening, and transported to the laboratory. The screened logs were stored at 4 °C until processed. The bark was stripped from each section using a drawknife. The presence and extent of stem attack and colonization by hickory bark beetles were recorded for each section. In addition, the numbers of visible xylem lesions typical of Ceratocystis canker of hickory (Park et al. 2010) were determined and any association with bark beetle attacks recorded.

Collection and Bioassay of Bark Beetles

Attacking bark beetles

Initial hickory bark beetle attacks were detected on bitternut hickory with actively declining crowns in Minnesota and two of the Wisconsin (Marathon and Shawano County) field sites. Between 26 August and 2 September 2009, five of six trees were felled to facilitate collection of bark beetle adults as they were constructing entry tunnels; ladders were used to collect from the sixth tree. The outer bark was carefully scraped around the entry hole and needle probes were used to gently push each individual adult beetle from its entry tunnel and into a 1.5 ml micro-centrifuge tube. Captured bark beetles were grouped by source tree number and geographical location and stored on ice for transport to the laboratory where beetles were sexed and then stored at -10 °C until further processed.

Emerging Bark Beetles

Based on prior experience and the literature (Goeden and Norris 1964), hickory bark beetles were known to start emerging from colonized bitternut hickory in mid to late June in Wisconsin. In order to sample colonized trees prior to emergence, actively declining trees were identified in mid-June of each collection year. In 2010, two trees were felled and stems examined for entry holes of the beetle from late summer 2009 attacks. A drawknife was used to expose galleries associated with holes and any adults beetles were carefully removed with insect forceps. These captured, “excavated” beetles were stored as previously described for attacking bark beetles. In 2009, three actively declining trees in Shawano Co., WI, and four in Marathon County, WI, were felled and stems closely examined for evidence of hickory bark beetle activity. Two to three 0.7-m-long stem sections were removed from colonized portions of each tree, each section was wrapped and sealed in insect screening, and all were transported to the laboratory. Each stem section was placed into a 1 m long by 38 cm diameter cardboard tube with aluminum screening on the outside and the ends sealed with plastic caps. Emerged bark beetles were obtained from the collection cup protruding from the side of the tube. Collections were made twice per week until no further adult emergence occurred. The collected bark beetles were counted, sex identified, and stored singly in micro-centrifuge tubes as previously described.

Bioassay of Bark Beetles

Bark beetles were assayed for the presence *C. smalleyi* on their exoskeleton using either serial dilution plating techniques or polymerase chain reaction (PCR) and cloning techniques. Serial dilution plating detects only the viable fungus propagules present while the PCR method amplifies DNA of living and dead fungi that are present. Sterilized water (0.5 ml) was added to each microcentrifuge tube containing a single bark beetle, and the suspension was subjected to sonication (10 seconds) using a tip sonicator (Ultrasonic Homogenizer, Cole-Palmer, Vernon Hills, IL) to dislodge fungal propagules present on the exoskeleton of each bark beetle. The resulting solution was then serially diluted (3X), and 0.5 ml aliquots of each dilution were spread onto 2 percent malt yeast extract agar amended with 100 ppm streptomycin sulfate in petri dishes. The plates were stored in an incubator (dark conditions, 24 °C) for 14 days. The number of *C. smalleyi* colonies were then determined and recorded. Identification of the fungus was based on culture morphology, presence of perithecia and extruding ascospores, and characteristic endoconidia (Johnson et al. 2005). All bark beetles were processed within 3 months of capture. PCR and cloning were used to detect the presence of viable or nonviable propagules of the fungus on a different subset of beetles from the attacking and emerged beetle collections. The fungal DNA associated with 26 attacking and 21 emerged bark beetles was extracted. Each bark beetle was transferred from its storage tube to a sterile 1.5 mL centrifuge tube, 200 µL of cell lysis buffer (Lindner and Banik 2009) was added, and each tube was sonicated as previously described. The tubes were then heated at 65 °C for 1 hour, centrifuged at 10,000 g for 5 min, and 100 µL of the supernatant was removed to a 200 µL strip-tube. The DNA from each sample was then precipitated with isopropanol and cleaned with glass milk (Lindner and Banik 2009). The cleaned DNA was suspended in 50 µL molecular grade water and used as template DNA for PCR. The ITS (internal transcribed spacer) region of the DNA was amplified using the fungal specific primer pair ITS1F and ITS4. The PCR reaction protocol, thermal cycler parameters, and cloning methodology used were those of Lindner and Banik (2009). Either 8 or 16 bacterial colonies which had been successfully transformed with PCR products were re-amplified in PCR as before. The resulting PCR products were diluted approximately 1:10 with molecular grade water and cycle sequenced per methods in Lindner and Banik (2009). The resulting sequences were compared against known *C. smalleyi* ITS sequences using Sequencher® version 5.0 sequence analysis software (Gene Codes Corp., Ann Arbor, MI).

Hickory Inoculation and Canker Evaluation for Sap Flow Study

Fungus Inoculation

To mimic the natural occurrence of multiple cankers on bitternut hickory, multiple sites on stems of each study tree (between 13 and 28 cm d.b.h.) were inoculated with *C. smalleyi*. In July 2008, 50 holes (0.6 cm diameter) were made by drilling into the outer sapwood on the main stem of nine healthy bitternut hickory trees between 1.8 and 3.7 m stem height in Wabasha County, MN. The holes were mostly situated in four longitudinal lines, one on each cardinal aspect of the tree. Aliquots (0.1 ml) of *C. smalleyi* spore suspensions (1.0×10^4 ascospores/ml) of two locally-derived isolates and of sterile distilled water (control) were placed into the drilled holes (Park et al. 2010). Each hole was sealed with moist cotton and moldable putty. Noninoculated trees (three) served as negative controls. In July 2009, the same methods were used to repeat the experiment in Chippewa County, WI.

Canker Evaluation

Stems of the fungus and water inoculated trees were examined for presence of visible cankers 12 to 14 months after treatment. Once sap flow measurements were completed, the bark around each inoculation hole was stripped using a drawknife, and the extent of inner bark necrosis was recorded. Using the estimated area of each canker and total area of the bark for the 1.9 m long stem section receiving treatments, the proportion of the total stem area with cankered tissues was calculated for each tree. Wood samples that contained the edges of four cankers or inoculation wounds (for water controls) were taken from each tree to verify the presence of *C. smalleyi.* Small wood cubes were cut from each sample and placed in small moist chambers to stimulate fungus sporulation. Ascospore masses exuded from perithecia formed on the cubes were transferred to 2 percent malt yeast extract agar amended with 100 ppm streptomycin sulfate to obtain fungal isolates.

Measuring Sap Flow Rates

Granier-type thermal dissipation probes (TDP) and their associated system were used to monitor sap flow rate (Js) of each study tree (inoculated and noninoculated). Using these techniques, reduced sap flow velocity has been observed with sudden oak death in tanoak (*Lithocarpus densiflorus*) (Parke et al. 2007) and transpiration in deciduous broadleaf trees monitored in a suburban landscape (Peters et al. 2010). Each probe consists of a heated and an unheated sensor, and the signal recorded is the temperature difference between the two sensors. To prevent thermal interference, the heated sensor was installed 4 cm above the unheated sensor as recommended by the manufacturer (Dynamax Inc., Houston, TX). The temperature difference is dependent on the rate of sap flow around the probes. As sap flow rates increase, heat is dissipated more rapidly and the temperature differences decrease (Smith and Allen 1996).

For the Minnesota experiment, probes were installed on four fungus-inoculated, one water-inoculated, and two noninoculated trees in mid-September 2009. Three 3-cm-long manufactured probes (Dynamax Inc., Houston, TX) were inserted radially into the sapwood approximately 30 cm above the uppermost inoculation points on each tree stem. Two probes were located above two of the inoculation "columns" while the third was placed between the two columns. To prevent rain water from reaching the probes, silicone was applied to the probe-sapwood interface, and a plastic cup covered each sealed probe. Reflective bubble wrap applied around the stem at probe height provided thermal insulation. Signals from the sensors were monitored every 15 seconds, and 30 minute means were recorded by a data logger (CR 10X, Campbell Scientific, Inc., Logan, UT) for 18 days. For the Wisconsin experiment, probes were installed on five fungus-inoculated, three water-inoculated, and three noninoculated trees in late July 2010. However, two 2-cm-long, hand-made probes and one 3 cm long manufactured probe were used for each tree. As in Minnesota, the probes were placed 30 cm above the uppermost inoculation points, but in Wisconsin all three probes were placed above inoculation columns.

The sap flow rate, J_s in g H_2O m^{-2} s^{-1}, was calculated according to Granier's equation (Granier1987):

$$J_s = 119\left(\frac{\Delta T_M - \Delta T}{\Delta T}\right)^{1.231}$$

Where ΔT (°C) is the mean temperature difference between sensors during each half-hour measurement interval. The value of ΔT_M is determined when ΔT_M is at the peak over each 24 h cycle.

The software package BaseLiner (version 2.4.1, Hydro-Ecology Group, Duke University, Durham, NC) was used to calculate ΔT_M and J_s . The equation was calibrated in case the sapwood depth is shorter than the probe length (Lu et al. 2004).

Canker Development Evaluation and Sampling for Colonization Study

Fungus Inoculation and Temporal Sampling

Two locally derived isolates of *C. smalleyi* were grown on 2 percent malt yeast extract agar. and extruded masses of ascospores were transferred from tips of perithecia to 1.0 ml sterile distilled water. The suspension was homogenized using a tip sonicator, and the resultant suspension was adjusted to a concentration of 1×10^4 ascospores/ml. In late June 2008, four holes (6 mm diameter) were drilled into the outer sapwood around the circumference of each tree, and 0.1 ml of the inoculum was placed into each hole. Moist cotton and masking tape was used to cover the inoculated holes. Four *C. smalleyi* inoculated and two sterile water inoculated tree were evaluated at 2 months postinoculation; two *C. smalleyi* inoculated trees only were evaluated at 12 months. There were four inoculation points per tree in all cases. Stem sections (1.0 m in length) containing the four inoculated points were cut from the inoculated trees at 2 and at 12 months, wrapped and sealed for transport to the laboratory, and stored at 4 °C until further processed.

Sample Processing

Each stem section was examined for symptoms of diffuse bark cankers and xylem lesions/discoloration. A drawknife was used to remove the outer bark so inner bark lesions could be measured. Using a band saw, sections were then quartered along the longitudinal axis to separate each canker or control wound. Length of discolored sapwood associated with each inoculation point was then recorded. Stem slices were removed from the longitudinal ends of xylem lesions resulting from the inoculations. Small wood cubes were cut from these slices and attempts made to re-isolate the fungus (as previously described). Subsamples were also taken for histological study. Three 2-cm thick wood slices were cut at 2, 12, and 22 cm from each inoculation point. Wood cubes (1.5 cm by 1.5 cm by 2 cm) were subsequently obtained from the interface between clear and discolored sapwood of these wood slices and fixed in formaldehyde: acetic acid: ethanol solution prior to sectioning.

Histological Evaluations of Sapwood

Observations and Measurements for Sap Flow Study

Three measurements (mean vessel diameter, mean hydraulic vessel diameter, and size distribution of vessels) were made to determine if any intrinsic differences in vessel sizes existed that could have affected water conduction in study the trees. Two sapwood cubes (1.5 cm by 1.5cm by 2.0 cm) were taken from above and below each probe location. Cross sections (20-25 µm) were collected from each wood cube using a sliding microtome (Model 860, American Optical, Southbridge, MA), were stained in toluidine blue O (0.5 percent aqueous), and were mounted in 10 percent glycerol. Five hundred vessels were analyzed for each problem location (250 vessels for each wood cube). Vessel diameters were measured at 100x magnification using imaging software (NIS-Elements, Nikon Instruments Inc., Melville, NY). Mean diameters for treatment group was calculated by averaging vessel diameters obtained for every probe location on trees within the group. Mean hydraulic vessel diameter also was calculated for each treatment as $\sum d^5/\sum d^4$. Frequency distributions of vessel diameters were based on 30 um diameter classes using measurements for 500 vessels for each probe location within each treatment group. Tylose formation was observed at 100x magnification with the same cross sections used for vessel diameter measurements. The number of vessels with and without tyloses in each annual ring from the current-year ring back to the 9th or 10th ring from the current-year ring was counted (n = 500 per probe location).

Observations and Measurements for Fungus Colonization Study

Of the two wood cubes obtained from sampled points at increasing distance from the inoculation point, one was sectioned transversely and the other longitudinally to a 20 to 25 um thickness using a sliding microtome. The occurrences of fungal hyphae, tyloses, and gels in vessels were observed by light microscopy of transverse sections stained with toluidine blue O mounted in 10 percent glycerol. For each section, 250 vessels were examined and numbers recorded for: 1) occluded vessels with tyloses or gels, 2) nonoccluded but fungus-colonized vessels, and 3) nonoccluded, sound vessels.

Data Analyses

For both fungus colonization and sap flow studies, one-way analysis of variance (ANOVA) was used to test for differences between inoculum type and the average size of inner bark cankers. When the F-statistic was significant, differences in means were determined using Tukey's HSD ($\alpha = 0.05$). The averages of maximum sap flow rate measured on multiple days were estimated for each tree by repeated measures ANOVA. Two-sample t-tests (at 95 percent confidence level) were used to compare mean maximum flow rate, mean vessel diameter, mean hydraulic vessel diameter, and tylose abundance to those of control trees. Pearson's chi-square statistics ($\alpha = 0.05$) were used to detect significant correlation among mean maximum sap flow rate, proportion of cankered bark, and selected xylem features. Linear regression analyses also were used to investigate relationships between these same variables. For the fungus colonization study, mean percentages of occluded, fungus-colonized, and sound vessels of fungus inoculated trees 2 and 12 months after inoculation with *C. smalleyi* or sterile water were compared using two sample t-tests for means (95 percent confidence level). All statistical analyses were conducted using SAS 9.1 (SAS Institute, Inc. Cary, NC).

RESULTS

Hickory Bark Beetle-*Ceratocystis smalleyi* Association on Declining Trees

Hickory Bark Beetle Attacks and Canker Occurrence

Debarking of the main stems of three bitternut hickories exhibiting active crown decline revealed attacks by hickory bark beetles characterized by aborted to fully successful colonization (i.e., full gallery system) (Table 1). No clear relationship was observed between total number of bark beetle attacks (178; 1,448; 991) and active crown decline rating (40, 55, and 80 percent). The proportions of successful colonization based on total numbers of attacks were 92, 53 and 80 percent on the actively declining trees (40, 55, and 80 percent rating, respectively).

Bark cankers and/or xylem lesions were associated with less than 40 percent of the total number of hickory bark beetle attacks (Table 2). The estimate of cankers/lesions is conservative, however, for the tree with 55 percent decline. Evidence of bark beetle attacks were apparent on most 1-m stem sections for this tree, but the cambial region of several sections was uniformly discolored and discrete lesions could not be detected. The mean lengths of the observed xylem lesions on each bark-stripped tree were 8.2, 5.1, and 7.1 cm on the stripped trees (40, 55, and 80 percent crown decline rating, respectively). In all cases, the observed lesions extended beyond the edges of the bark beetle gallery systems when present. *C. smalleyi* is commonly isolated from these types of xylem lesions (Park 2011), but this variable was not assessed for the three trees.

C. *smalleyi* Presence on Hickory Bark Beetles

Only female beetles were captured by probing the entry tunnels that each was constructing during their initial attacks of six bitternut hickories in two northern Wisconsin and one southeastern

Table 1.—Number of adult hickory bark beetle attacks by extent of beetle colonization on three bitternut hickory trees exhibiting active crown decline

Tree number	Location	Tree size d.b.h. (cm)	Tree size height (m)	Percent crown decline	Extent of beetle colonization by category: entry tunnel only	tunnel plus egg gallery	full gallery system[a]
1	Chippewa Co., WI	26.7	21.3	80	30	27	934
2	Marathon Co., WI	23.7	21.4	55	401	276	771
3	Marathon Co., WI	22.9	26	40	13	1	164

[a]Full gallery system includes entry tunnel, full egg gallery and radiating larval tunnels.

Table 2.—Numbers of bark cankers and xylem lesions found on main stems of three bitternut hickory trees exhibiting active crown symptoms

Tree number	Location	Tree d.b.h. (cm)	Percent crown decline	Numbers of bark cankers and xylem lesions: Total	Associated with beetle attacks
1	Chippewa Co., WI	26.7	80	113	106
2	Marathon Co., WI	23.7	55	585[a]	551
3	Marathon Co., WI	22.9	40	26	24

[a]Cambium of stem sections with numerous hickory bark beetle attacks were dead and uniformly darkened in color; thus, it was not possible to detect xylem lesions with reddish-brown discoloration.

Table 3.—Number of adult hickory bark beetles on which *Ceratocystis smalleyi* was detected via serial dilution plating assay and molecular assay (PCR and cloning). The beetles were collected during their initial attacks on six bitternut hickories between late August and early September 2009.

Collection location	Number of sampled trees	Number of beetles collected	Serial dilution plating results: Number of beetles assayed	Serial dilution plating results: Number yielding *C. smalleyi*	PCR and cloning results: Number of beetles assayed	PCR and cloning results: Number with *C. smalleyi*
Wabasha Co., MN	1	19	19	2	--[a]	--
Marathon Co., WI	2	154	61	57	12	11
Shawano Co., WI	3	112	60	53	12	11

[a] -- denotes that no beetles were assayed.

Minnesota locations. All collections were made between 26 August and 2 September 2009. *C. smalleyi* was isolated from bark beetles collected from all six trees using serial dilution plating, but isolation frequencies differed by site (Table 3). Isolation rate was lowest for the Minnesota site (11 percent) compared to the Wisconsin sites (88 and 93 percent). Similar results (92 percent pathogen positive) were found using PCR and cloning on washings from a subset (n = 24) of the Wisconsin beetle collections (Table 3). Of 219 clones that were amplified from 24 attacking bark beetles, 93 yielded sequences of *C. smalleyi* (data not shown).

Both male and female beetles (n = 43) were collected just prior to bark beetle emergence by excavation from the bark of two bitternut hickories (19 and 28.7 cm d.b.h.) exhibiting crown decline (50 and 80 percent decline ratings) in the Shawano County, WI, stand. Bark beetles were collected 18-19 June 2010. *C. smalleyi* was isolated from 7 percent of the beetles assayed for the fungus using serial dilution plating.

Table 4.—Proportion of bark area (within the inoculated stem zone) of bitternut hickory exhibiting bark cankers or other necrosis following multiple inoculations with *Ceratocystis smalleyi* prior to sap flow rate measurements

Study location	Treatment [a]	Number of trees	Cankered or necrotic bark area (percent) [b]	
			mean	range
Wabasha Co., MN	*C. smalleyi* inoculated	3	8.8	3.8 - 11.5
	water inoculated	1	0.9	--
	non-inoculated	2	0	--
Chippewa Co., WI	*C. smalleyi* inoculated	5	26.2	15.3 - 41.3
	water inoculated	3	1.3	0.6 - 2.2
	non-inoculated	3	0	--

[a] Aqueous suspensions (0.1 ml) of fungus ascospores were placed in 6 mm dia drilled hole into the outer sapwood; 0.1 ml sterile distilled water was used on water-inoculated trees.

[b] The sum of the areas of the 50 bark cankers (fungus inoculated trees) or necrosis associated with water inoculated wound was divided by the stem surface area in the inoculated height zone to estimate the diseased or necrotic portion of each stem's bark.

Numerous male and female bark beetles emerged from stem sections placed in emergence tubes. The sections were cut from three bitternut hickories (between 23 and 34 cm d.b.h.) exhibiting active crown decline in Shawano County, WI, and four trees (between 14 and 27 cm d.b.h.) exhibiting active crown decline in Marathon County, WI. The declining trees were felled and stem sections collected between 20 May and 19 June 2009. No *C. smalleyi* was isolated from any of the 120 bark beetles assayed using serial dilution plating. The same result was found using PCR and cloning on washings from a subset of the same beetle collections. Of 248 clones that were amplified from 21 emerged adult bark beetles, none yielded sequences of *C. smalleyi* (data not shown).

Effect of Cankers on Tree Sap Flow Rate

Proportion of Inoculated Stems with Bark Cankers

Twelve to fourteen months after *C. smalleyi* inoculation, the sap flow study trees exhibited large bark cankers and accompanying xylem lesions compared to very small necrotic areas on water controls (Table 4). The mean size (area) of the cankers on the Wisconsin trees (64.3 ± 2.2 cm^2) was larger than that on the Minnesota trees (15.3 ± 0.6 cm^2) ($P < 0.0001$). The sum of the areas of the 50 bark cankers on each tree was calculated and divided by the stem surface area in the inoculated zone to estimate the proportion of each diseased stem. The proportions calculated for the fungus-inoculated trees were variable (up to 11.5 percent in Minnesota and 41.3 in Wisconsin), but clearly much larger than necrotic bark areas on water-inoculated control trees (< 2.2 percent) (Table 4).

Diurnal Patterns of Sap Flow Rates

Similar diurnal trends of sap flow were found for all the trees (Fig. 1). Sap flow rate was highest just after 12 noon and lowest through the nighttime. Lower sap flow rates during midday were found for the *C. smalleyi* inoculated trees compared to the water inoculated controls.

The maximum values of sap flow rate on a representative number of days within the measurement period were lowest for the fungus-inoculated trees (10.7 to 18.1 g $m^{-2}s^{-1}$ in Minnesota and 5.7 to 27.2 g m^{-2} s^{-1} in Wisconsin) compared to the control trees (26.3 to 30.0 g m^{-2} s^{-1}, Minnesota; 34.2 to

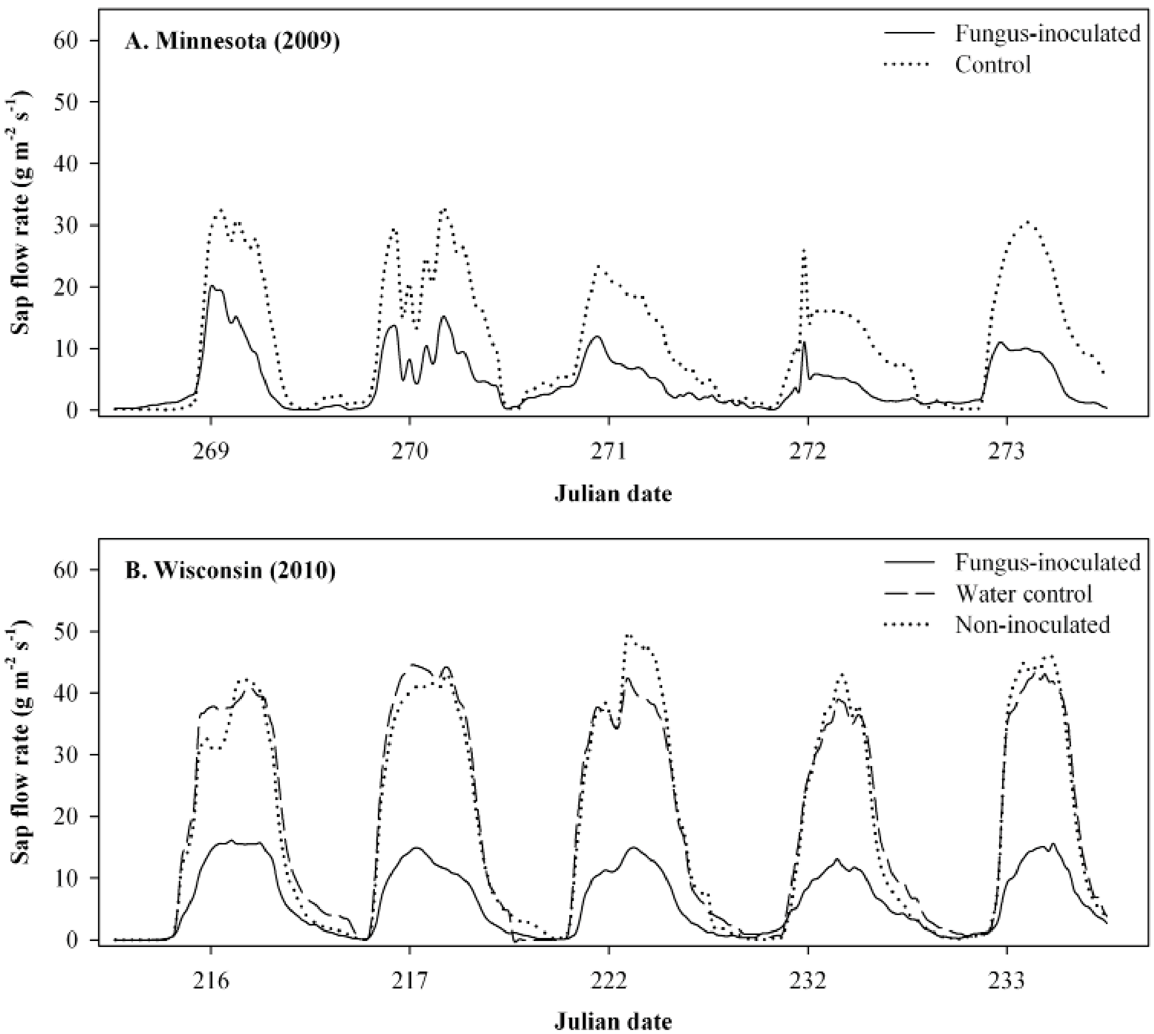

Figure 1.—Diurnal patterns of sap flow rates in bitternut hickory trees (13 to 28 cm d.b.h.) inoculated with *Ceratocystis smalleyi*. Measurements displayed are a subset of the longer time period during which sap flow was measured and recorded.

49.3 g m^{-2} s^{-1}, Wisconsin) (Fig. 1). In Minnesota, the average maximum sap flow rate of all infected trees (14.0 ± 2.1 g m^{-2} s^{-1}) was 51 percent lower than the average maximum value for the control trees (28.6 ± 1.1 g m^{-2} s^{-1}) (P = 0.009). In Wisconsin, the average maximum sap flow rate of all infected trees (15.3 ± 3.8 g m^{-2} s^{-1}) was 64 percent lower than the mean maximum value for all the control trees (41.9 ± 2.2 g m^{-2} s^{-1}) (P=0.0001). The sap flow rates were consistently lower in the Minnesota trial than the Wisconsin trial, but this was likely due to the differences in time of year during which measurements were made, i.e., early fall in Minnesota versus midsummer in Wisconsin.

Tylose Abundance, Cankered Stem Area and Sap Flow Rate Relationships

Differences in vessel diameters between inoculated trees and control trees were insignificant (P ≥ 0.19) (data not shown). Vessel diameter distributions of the inoculated trees and the controls were also similar (P = 0.23). Tyloses were observed within vessels of all the trees, but they were more abundant in the *C. smalleyi* inoculated ones than the controls (P < 0.006) in both the two outer annual rings (9 percent, controls; 30 to 56 percent, fungus-inoculated) and the outer 9 to 10 outer annual rings (25 to 42 percent, controls; 37 to 59 percent, fungus-inoculated). The difference in

Table 5. —Mean length and width of inner bark lesions and mean length of discolored sapwood on *Ceratocystis smalleyi* inoculated bitternut hickory 2 and 12 months after treatment

Time after inoculation (months)	Inoculum	Number of trees	Total number of inoculation points	Mean inner bark lesion dimension (cm)		Discolored sapwood
				width +/- SE	length +/- SE	length (cm) +/- SE
2	*C. smalleyi* [a]	4	16	2.6 ± 0.08	21.8 ± 2.64	23.6 ± 2.84
2	sterile water	2	8	0.2 ± 0.02	0.2 ± 0.02	0
12	*C. smalleyi*	2	8	3.0 ± 0.09	64.2 ± 3.20	68.0 ± 3.27

[a] Data were pooled from inoculated trees with two *C. smalleyi* isolates (CS0731 and CS0734).

tylose abundance between treatments was more pronounced in the outer two annual rings ($P = 0.0012$, Minnesota; $P < 0.0001$, Wisconsin). Tyloses rarely formed in the most recent xylem vessels in the absence of fungal infection. *C. smalleyi* inoculated trees had more vessels with tyloses in the outer 9 to 10 annual rings than the controls ($P < 0.006$) for both sites.

Correlation analyses revealed significant interactions between 1) average maximum sap flow rate and tylose abundance in the two outer annual rings ($P = 0.0084$) for both sites combined, and 2) tylose abundance in the same anatomical location and proportion of cankered bark ($P = 0.0045$) for both sites combined. Correlation analysis also revealed significant interactions between average maximum sap flow rate and proportion of cankered bark area ($P = 0.0042$). Specifically, an inverse relationship was found between percent of proportion of cankered bark area and average maximum sap flow rate in both sites based on linear regression analysis (Minnesota: $R^2 = 0.90$, $P = 0.0042$; Wisconsin: $R^2 = 0.90$, $P < 0.0001$).

Bitternut Hickory Stem Colonization by *Ceratocystis smalleyi*

Bark Canker Development

Long narrow cankers were evident two months after inoculation with *C. smalleyi* isolates while no cankers resulted from water (control) inoculation. Mean dimensions of inner bark cankers (length and width) were greater at 12 months than 2 months ($P < 0.05$) based on two-sample t-tests for means of measurements at each inoculation point (Table 5). Long narrow, reddish-brown discoloration of sapwood was associated with each fungus inoculated point. Wedge-shaped discoloration was evident in cross-sections of the stem samples. Wound callus formed over all water-inoculated points and no sapwood discoloration was found. In general, the length of the sapwood discoloration was larger than the corresponding inner bark lesion.

Visible Evidence of Fungus Infection in Sapwood

C. smalleyi was isolated from the margins of discolored and adjacent clear sapwood, i.e., the reaction zone or canker margin, and never isolated from sapwood associated with water-inoculation points. Using light microscopy and toluidine blue O stain, fungal hyphae were commonly observed and found to be abundant in the discolored sapwood at the canker margins. Hyphae were commonly observed in the different elements of the xylem tissue, e.g., axial and radial parenchyma cells, fibers, and vessels (Fig. 2 A and B). Furthermore, hyphae were found to grow through bordered

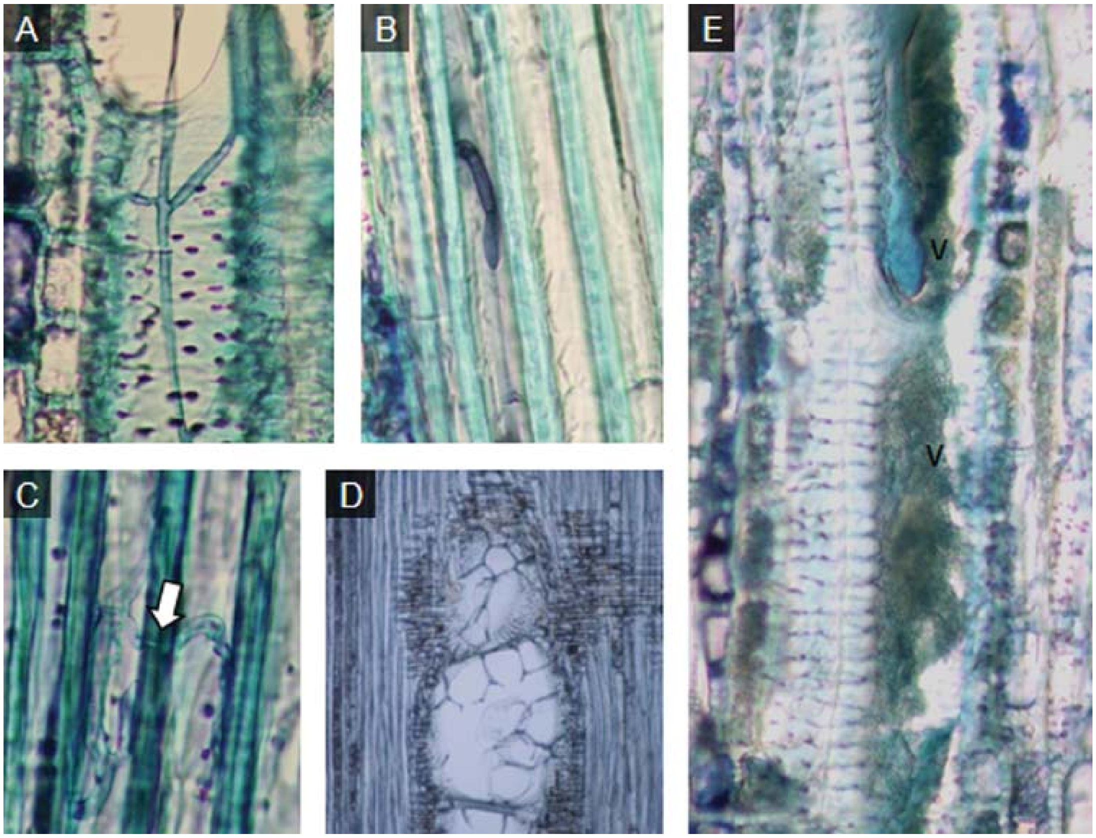

Figure 2.—Presence of *Ceratocystis smalleyi* and host responses to its colonization in sapwood of bitternut hickory. A. Branching of hyphae in a large vessel. B. Advancing hyphal tip in a wood fiber. C. Hyphal penetration of a bordered pit. D. Earlywood vessel showing contiguous tyloses in radial view. E. Gels formed in latewood vessel (V) and surrounding parenchyma cells in radial view. Sections A, B, C, and E were stained with toluidine blue O and section D was stained with Nile blue.

pits between neighboring cells (Fig. 2 C). No fungal hyphae were observed in sapwood of water inoculated trees. Fungal hyphae were observed in 0.4 to 12.4 percent of nonoccluded vessels in the reaction zone at 2 months and 0.4 to 34.7 percent of vessels at 12 months after treatment in fungus-inoculated trees. The mean proportion of fungus-colonized vessels was higher at 12 months (8.1 ± 2.1 percent) than at 2 months (2.1 ± 0.7 percent) ($P = 0.01$).

Xylem Occlusion by Tyloses and Gels

Tyloses were abundant in early-wood vessels of the fungus-inoculated trees and vessel lumens typically occluded by multiple, contiguous tyloses (Fig. 2 D). Gels partially or completely occluded late-wood vessels. When vessels were completely occluded, gel substances were observed commonly in parenchyma cells surrounding the affected vessel(s) (Fig. 2 E). Vessel occlusion occurred in response to both water and fungus inoculation, but was more abundant ($P < 0.05$) in *C. smalleyi* inoculated trees. No gel accumulation was observed in water-inoculated trees.

DISCUSSION

Nature of Hickory Bark Beetle–*C. smalleyi* Interaction

Based on the literature, death of hickory attributed to hickory bark beetles is caused by girdling of the main stem of the affected tree by coalescing galleries of the bark beetle (U.S. Forest Service 1985). Our observation, however, is that hickory bark beetle gallery systems do not coalesce on actively declining trees, and when *C. smalleyi* xylem lesions are associated with the galleries, the lesion areas in the cambium almost always exceeds the area occupied by the gallery system. Coalescing beetle galleries were observed on dead standing bitternut hickory during the 2007-2008 hickory survey (Juzwik et al. 2008b), but we suspect such extensive colonization of the bark occurs after 95 percent or more of the crown has died.

Based on results of studies presented in this paper and unpublished field observations, we propose that a synergistic interaction of hickory bark beetles and *C. smalleyi* is likely responsible for the observed rapid crown decline and subsequent death of affected, smooth-bark hickories. *C. smalleyi* was detected on a high percentage of attacking beetles collected from two of three field sites. In addition, reddish-brown inner bark and xylem lesions were often observed in mid-September on recently attacked trees (J. Juzwik, pers. observation). The adult bark beetle thus provides the entry and infection court for the fungus on susceptible hickories. Furthermore, the bark beetle may be responsible for dissemination and inoculation of the fungus into the bark beetle wounded tissues. The fruiting bodies (perithecia) of the homothallic fungus have been observed in galleries of the hickory bark beetle and the sticky spores produced by the perithecia are well-suited for acquisition by emerging beetles (Johnson et al. 2005). However, in this study dilution plating and PCR and cloning indicated that none of the assayed bark beetles that emerged from stems of heavily attacked, actively declining bitternut hickory yielded the fungus. Several explanations for this lack of pathogen detection include: the numbers of bark beetles assayed were too few to detect the fungus in the sampled population of beetles emerging from the trees, the beetle is not an important disseminator of the fungus, or the beetle acquires the fungus from another source following its early summer emergence from beetle-killed trees but prior to attack of other hickory in late summer. Additional study is needed to address these hypotheses and to determine if the insect is an important vector of the pathogen or merely provides an infection court.

Role of *C. smalleyi* in Rapid Crown Decline

Histological investigations associated with the sap flow study and the fungus colonization study demonstrated *C. smalleyi* infections in sapwood of bitternut hickory apparently induce tylose formation in xylem vessels and accumulation of gels in late-wood vessels and surrounding parenchyma cells. Both of these response mechanisms lead to occlusion of xylem vessels and obstruction of water transport in affected trees. Reduced sap flow rates in bitternut hickory with multiple stem infections apparently result from these obstructions. Multiple fungus infections and resulting host response can logically explain the symptom of rapid crown decline (and at times, foliage wilt) observed in affected trees.

Growth and spread of the fungus through xylem vessels may be responsible for canker resurgence observed on both naturally infected and artificially inoculated trees. This resurgence may account for the occurrence of xylem lesions and bark cankers that infrequently occur in the absence of hickory bark beetle attack on stems of affected bitternut hickory. Conspicuous lack of fungus spores in the xylem supports the observation that systemic spread of the pathogen throughout the tree (e.g., as occurs with *Ceratocystis fagacearum* in red oaks in development of oak wilt) does not occur. Furthermore, the long but restricted xylem lesions associated with *C. smalleyi* infection and the host response to infection (e.g., tylose occluded vessels) supports the hypothesis that the fungus is a limited vascular wilt pathogen in bitternut hickory. This situation is similar to that of *Raffaelea quercivora* infections of *Quercus crispula* and *Q. serrata* following ambrosia beetle attacks in the disease known as Japanese oak wilt (Kuroda 2001, Kuroda and Yamada 1996, Murata et al. 2005, Murata et al. 2007) and to *Phytophthora ramorum* infection of sapwood and host response in tanoak (Collins et al. 2009, Parke et al. 2007).

Hickory Decline as the Disease Name

Recent reports of dieback or of declining crowns of bitternut and shagbark hickory exist in the literature (Juzwik et al. 2008a, Wisconsin DNR 2005). The specific disease of rapidly declining crowns and mortality in smooth-bark hickory is an example of a previously described decline disease for which major determinants are now known (Ostry et al. 2011). Through sequential and systematic studies, we have demonstrated that mass attacks by hickory bark beetles and closely associated xylem lesions caused by the canker fungus, *C. smalleyi*, are the most common stem damage associated with actively declining bitternut hickory. With this new knowledge, we propose that the new name "Ceratocystis wilt of hickory" be formally used for this disease. This follows the history of a newly discovered disease of black walnut that was first described as walnut decline in the 1990s, but upon discovery of the primary biotic causes (walnut twig beetle and *Geosmithia morbida*) the name was changed to better describe the disease, i.e., thousand cankers disease (Tisserat et al. 2009).

In conclusion, declining crowns and death of hickory have been previously attributed to drought and subsequent hickory bark beetle attacks (U.S. Forest Service 1985) or to a decline disease of the species (Juzwik et al. 2008a, Wisconsin DNR 2005). Results from the series of related studies presented in this paper document the deleterious effects of multiple cankers and xylem dysfunction caused by *C. smalleyi* on the health of bitternut hickory. Furthermore, the synergistic interaction of the hickory bark beetle and *C. smalleyi* results in numerous bark cankers and debilitating xylem lesions on stems of bitternut hickory that we hypothesize leads to rapid crown decline and tree death, especially following predisposing abiotic events. Drought is still considered to be an important predisposing factor as it leads to hickory bark beetle population buildup.

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PRELIMINARY REPORT OF ECOLOGICAL FACTORS INFLUENCING INCIDENCE AND SEVERITY OF BEECH BARK DISEASE IN THE APPALACHIAN REGION

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Abstract.—Resistance to *Cryptococcus fagisuga,* a primary component of the beech bark disease (BBD) complex, is heritable. Reportedly about 1-2 percent of American beech (*Fagus grandifolia* Ehrh.) are genetically resistant to *C. fagisuga*. This project is designed to identify environmental factors contributing to BBD incidence and severity. Plots were established in stands with endemic BBD and a disease-free beech component. To date 1,479 beech trees have been sampled; 55 percent were scale-free or have trace infestation, and 79 percent were free of *Neonectria* infection. Twenty parameters were evaluated for correlations with infestation/infection. Correlation matrices identified factors possibly contributing to infestation and infection. The strongest correlations with infestation were slope (r= -0.235) and species composition of the canopy (r = -0.187). Beech height and *Neonectria* infection had the strongest correlation (r = 0.420); slope had the strongest negative correlation with infection (r = -0.344). Regression analyses estimated scale infestation was affected only by canopy composition (p = 0.034). Infection was impacted by beech height (p = 0.031), slope (p = 0.033), and ground coarse woody debris (CWD) species (p = 0.0001). Results indicate BBD-free beech appear on the landscape at rates much greater than expected, suggesting that environmental factors may influence disease incidence and severity.

INTRODUCTION

American beech (*Fagus grandifolia* Ehrh.) is the only native species of the genus *Fagus* in the United States, although local races and one variety may be recognized (Rushmore 1961). Considering its relatively low commercial value, American beech often is considered a nuisance species in forest management. However, the wood of beech is hard, strong, and useful for veneer, pulping, railroad ties, flooring, furniture, and food storage (Carpenter 1974). Its value as a fuelwood is nearly equal to white oak (Mielke et al. 1987). Beech is important ecologically as a climax species (Halls 1977) and resource for wildlife (Jakubas et al. 2005, Storer et al. 2005).

Beech bark disease (BBD) is a canker disease affecting bark tissues. It is a complex of interacting causal agents, primarily the beech scale (*Cryptococcus fagisuga* Lindinger) and several species of ascomycetous fungi now classified in the genus *Neonectria*. Both insect and fungus can injure beech individually, but serious damage does not occur without their combination (Shigo 1964). The disease has been known in Europe since the 1700s (Ehrlich 1934). There it is of concern because of its widespread effects on beech plantations, but in forest stands it more often is innocuous with small disease pockets developing around a single infected inoculum source.

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European beech (*Fagus sylvatica* L.) enjoys a substantial level of resistance to BBD that has either evolved as a natural trait in the species or from extended relationships with causal agents (Wainhouse and Howell 1983). The mortality of single or small groups of beech during disease development in Europe contrasts with the death of whole stands in North America. Resistance studies of sibling and clonal European beech reveal genetic control of beech scale resistance. Since the late 1800s, the beech scale has been known in North America, and by the 1920s, its complex with species of *Neonectria* was established in Canada and New England (Houston 2005). Currently the disease is spreading through Ohio, Pennsylvania, Virginia, and West Virginia. Outlying infections in Michigan, North Carolina, and Tennessee also are known (Morin et al. 2005). Beech bark disease has reached less than 30 percent of the range of beech while spreading an estimated 14.9 ± 0.9 km per year (Morin et al. 2007). Spread of the disease in North America is widely considered frontal in nature; accumulating populations of causal agents in an advancing front are followed by a killing front of widespread, heavy mortality and then an aftermath of defective sprout thickets, and occasionally, a few large survivors (Shigo 1972).

Despite an overall frontal nature of spread, BBD does not operate strictly on a frontline. In the last 20 years, 10 cases of isolated pockets of scale infestation ahead of an advancing front have been documented (Morin et al. 2007). Often, BBD progresses as a conglomeration of eruptive centers of disease emanating from randomly distributed inoculation sources. Whatever the case, the establishment of the disease in a stand is dependent on beech scale infestation (Houston 1994). The *Neonectria* fungal component of the BBD complex is an opportunistic weak pathogen capitalizing on the activities of the beech scale whose infection can normally be contained by defenses of healthy hosts (Houston 1980, Manion 1991).

For many years, some beech trees have been observed to escape both signs and symptoms of disease (Ehrlich 1934; Houston 1983; Shigo 1962, 1964; Wainhouse and Howell 1983). Studies of sibling and clonal European beech reveal resistance to beech scale is genetically controlled (Wainhouse and Howell 1983). Beech scale challenge trials confirm a small percentage of American beech (~1-2 percent) is genetically resistant to scale infestation (Koch and Carey 2004, Koch and Carey 2005).

This project is designed to determine whether ecological factors are related to the incidence of disease-free American beech. Specific objectives are to: 1) examine stand features including incidence and severity of BBD, species composition, stand density, canopy features, management activities, and BBD longevity; 2) measure landscape and topographical features including climate, slope, aspect, and elevation; and 3) evaluate other forest components including coarse woody debris (CWD) load, litter layer, soil types, and mycorrhizal associations.

STUDY AREAS

Seven Appalachian hardwood stands with a several-decade history of BBD and a component of disease-free beech have been sampled (Table 1). Data collection was completed at five West Virginia sites and partially completed at Kumbrabow State Forest and Great Smoky Mountains National Park. Sites at the Holden Arboretum in northeast Ohio and the Allegheny National Forest in north central Pennsylvania have been selected for study based on preliminary visits. Upcoming reconnaissance may identify additional sites in Maryland and West Virginia.

Table 1.—Study sites in the Appalachian region

Location	Number of plots
Shaver's Fork Recreation Area, Monongahela National Forest, WV	10
Gaudineer Scenic Area, Monongahela National Forest, WV	10
Middle Mountain, Monongahela National Forest, WV	10
Blackwater Falls State Park , WV (I)	7
Blackwater Falls State Park , WV (II)	6
Kumbrabow State Forest, WV	10
Great Smoky Mountains National Park, TN	6

Table 2.—Detailed descriptions of *Cryptococcus* infestation and *Neonectria* infection categories

Category	*Cryptococcus*	*Neonectria*
0	No beech scale evident	No *Neonectria* evident
1	Trace scale population; tree initially looks scale-free but infestation evident upon close inspection, may need hand lens	Trace *Neonectria*; tree initially looks infection-free but cankers or perithecia evident upon close inspection; may need hand lens
2	Beech scale clearly evident from a short distance; scales singular or uniformly dispersed in clusters; majority of stem scale-free	Cankers/perithecia clearly evident from short distance; few scattered or clusters of cankers; majority of stem infection-free
3	Beech scale clearly evident from a short distance; scales singular or uniformly dispersed AND in small clusters OR many clusters of scales; majority of stem may or may not be scale-free	Cankers/perithecia clearly evident from short distance; cankers litter large portion of stem; majority of stem likely cankered; streaks may appear; bark may be peeling off in small sections
4	Beech scale clearly evident from short distance; large clusters of scales all over stem; majority of stem likely infested	Cankers/perithecia clearly evident from short distance; cankers affect nearly entire stem; multiple streaks; bark may be peeling off in small sections; tree dead?

METHODS

Field Sampling

At each study site circular 0.04 ha plots were established in a northeast-southwest direction about 80-100 m apart. Variations of this design where employed as necessary to include beech in study plots. Plot centers was marked with pin flags and boundaries were marked in the cardinal directions. The slope, aspect, and elevation of each plot were recorded. Canopy density was estimated at several points in a plot using a concave spherical densiometer (Forest Densiometers, Bartlesville, OK). Basal area (BA) was estimated from the plot center using a basal area factor (BAF) 10 (~1 m^2/acre BA). A TruPulse 360° laser rangefinder (Laser Tecnology Inc., Centennial, CO) was used to establish distances from plot centers. Total height, canopy class, and diameter at breast height (d.b.h.) were recorded for all beech > 5 cm d.b.h. and non-beech >10 cm d.b.h. Scale infestation and *Neonectria* infection were rated separately on four sides of each beech using a qualitative five-category rating system of no infestation/infection (0), trace infestation/infection (1), light infestation/infection (2), moderate infestation/infection (3), or heavy infestation/infection (4). Detailed descriptions of categories are displayed in Table 2. Mean infestation/infection ratings were calculated for each tree from ratings on four sides and calculated for plots from mean ratings of all beech in each plot. Bark samples with *Neonectria* perithecia were collected for laboratory examination and processing. Samples were collected with a 1.3 cm diameter leather punch from three beech trees within each plot or nearby if necessary. Severely cracked, blocky, or blistered bark was sampled using the same methodology.

Table 3.—Parameters related to beech, non-beech trees species, overall tree species composition, and site features used as independent variables in regression analyses

Beech	Non-beech species	Overall species	Site features
Beech per ha	Non-beech stems per ha	Trees per ha	Volume CWD
Beech basal area per ha	Non-beech species basal area per ha	Basal area per ha	Volume standing CWD
Mean beech d.b.h.	Mean non-beech species d.b.h	Mean overall d.b.h.	Aspect
Mean beech height	Mean non-beech species height	Percent intermediate crown class species	Slope
Percent beech	Percent dominant/codominant non-beech		Canopy density
	Most abundant non-beech species (percent)		

Coordinates of beech stems were recorded with a Mobilemapper™ CE (Magellan Corp., Deerfield, IL) for digital mapping. Coarse woody debris (CWD) was measured on 13 m transects from plot center to the north and east boundaries. Diameter, species (if known), and decay level were recorded for debris crossing transects and greater than 1 cm diameter. All standing dead stems and stumps > 10 cm were counted as standing CWD and their height, species (if known), diameter measured at breast height or the stump's highest point, and decay level were recorded. Debris decay was recorded at four levels: sound wood with or without bark (1); sapwood decayed (2); sapwood and some heartwood decayed (3); or decayed throughout (4).

Laboratory Procedures

Neonectria samples recovered from bark plugs were identified to species using ascospore morphology as described by Castlebury et al. (2006). Perithecia were slide mounted in water under a Leica EZ 4 stereoscope (Leica Microsystems Inc., Buffalo Grove, IL) and ascospores viewed at 400x-1000x magnification with a Nikon Eclipse E600 light microscope (Nikon Instruments Inc., Melville, NY). Perithecia and bark tissues, sampled from plugs with a bone biopsy tool were surface sterilized in 10 percent bleach for 5-10 minutes and placed on Difco™ potato dextrose agar to isolate *Neonectria* species and other fungi. The confirmation of *Neonectria* samples will be by molecular analysis.

Statistical Analyses

An Excel 2010 (Microsoft®, Redmond, WA) database compiled from field sampling describing stand features including species composition and density, canopy, topography, forest floor, and bark organisms was analyzed for significant relationships with scale infestation and *Neonectria* infection. Proportions of beech with a given infestation or infection rating, or both, were calculated in Excel as a percent of total beech sampled. Mean ratings of infestation and infection for individual beech were rounded to the nearest whole number to fit each beech into a category. All other statistical analyses were performed in JMP 9.0® (SAS Institute Inc., Cary, NC). Twenty parameters (Table 3) were evaluated for correlation with mean beech scale and *Neonectria* ratings using plots as the sampling units. Scatterplot matrices and correlation coefficients generated in JMP identified those parameters that may have a relationship with scale infestation or *Neonectria* infection. Forward stepwise regression with minimum BIC stoppage and combine rules for control settings analyzed the individual and additive effects of parameters on infestation and infection rates. Regression analyses were performed on continuous and categorical data separately.

Table 4.—Categories of non-numerical parameters

Category	Dominant/ codominant non-beech	Intermediate/ suppressed non-beech	Most abundant non-beech	Ground CWD species	Standing CWD species	Aspect
1	Maples	Maples	Red/sugar maples	Beech	Beech	N
2	Maples/ hardwoods	Hardwoods	Other maples	Unknown	Unknown	NE
3	Yellow birch	Hardwood mix	Yellow birch	Beech/ unknown	Beech/ unknown	E
4	Hardwoods	Hardwood/conifer mix	Hardwoods	Hardwood	Hardwood	SE
5	Conifers	Conifers	Conifers	Hardwood/ conifer	Hardwood/ conifer	S
6	--	--	--	Conifer	Conifer	SW
7	--	--	--	--		W
8	--	--	--	--	--	NW

With the exception of aspect, all non-numerical data were grouped and analyzed in categories representing individual species or roughly defined forest cover types (Table 4). For example, dominant/codominant species compositions were grouped in five categories; maples (*Acer* spp.), maples/other hardwoods, yellow birch (*Betula alleghaniensis* Britton), miscellaneous hardwoods, and conifers. Aspect was analyzed in eight categories representing compass headings. Volumes of CWD were calculated as cubic meters per hectare for each plot with a line intersect sampling formula ($V = (\pi^2 10000/80000L)(\sum d^2)$) where L = length of sample line in meters and d = diameter in centimeters of woody debris intersecting the sample line. Standing CWD volumes were calculated as volumes of a cylinder ($V = r^2HT$) in cubic meters, summed, and converted to cubic meters per hectare for each plot.

RESULTS

Infestation and Infection Rates

To date, 1,479 beech have been sampled. Considering only scale infestation, 14 percent of beech were scale-free, 41 percent had trace infestation, and another 41 percent had light infestation (Table 5). Individual assessment of *Neonectria* infection indicates 79 percent of beech had no infection, 7 percent had trace infection, and 6 percent had light infection (Table 5). When evaluating disease as a combination of infestation and infection, 13 percent of the beech trees were free of both scale infestation and *Neonectria* infection, 37 percent had trace infestation and no infection, and 29 percent were lightly infested but not infected (Table 6). Overall, disease-free to lightly infested/infected beech appear in the highest proportions, but heavily diseased trees do persist, some with both heavy infestations and infections.

Table 5.—Percent of beech at all study sites (N = 1,479) exhibiting an individual *Cryptococcus* or *Neonectria* rating

Rating	*Cryptococcus*	*Neonectria*
0	14	79
1	41	7
2	41	6
3	3	4
4	1	2

Table 6.—Percent of beech at all study sites (N = 1,479) exhibiting combined ratings of *Cryptococcus* infestation and *Neonectria* infection

	Cryptococcus rating				
Neonectria rating	0	1	2	3	4
0	13	37	29	2	<1
1	<1	2	3	<1	0
2	<1	1	4	<1	<1
3	<1	1	4	<1	<1
4	<1	<1	1	0	<1

All *Neonectria* samples from Gaudineer Scenic Area and Shaver's Fork Recreation Area have been identified as *Neonectria faginata* (M.L. Lohman, A.M.J. Watson & Ayers) Castl. & Rossman based on ascospore morphology. Although light disease levels predominated, there were heavily infested/infected beech, and there was evidence of past beech mortality in CWD. American beech accounted for 65 percent of dead stems; another 11 percent of dead stems were unknown species. Furthermore, beech dominated ground CWD on 29 percent of the plots, and species of CWD were unknown on 47 percent of the plots.

Correlation Analysis

Correlation matrices and coefficients of twenty parameters identified those that most likely influenced *Cryptococcus* infestation and *Neonectria* infection. Larger absolute values for correlation coefficients indicate stronger relationships, and negative correlations indicate inverse relationships. Taller beech may incur more scale infestation (r = 0.1603) and *Neonectria* infection (r = 0.420) and a larger mean beech d.b.h. may correlate with increased *Neonectria* (r = 0.357) (Fig. 1). Considering all tree related factors, higher canopy density (r = 0.387) and larger overall mean d.b.h. (r = 0.278) may correlate with increased infection (Fig. 2). Scale infestation (r = -0.235) and infection (r = -0.344) may increase as slope decreases (Fig. 2). Increases in standing CWD volume may contribute to increased infection (r = 0.384), and as non-beech species density increases, infection may decrease (r = -0.259) (Fig. 3). *Neonectria* infection may be negatively affected by ground CWD species (r = -0.308), and scale infestation by canopy composition (r = -0.187) (Fig. 4). Some of these factors may significantly contribute to BBD severity individually or when combined with other parameters.

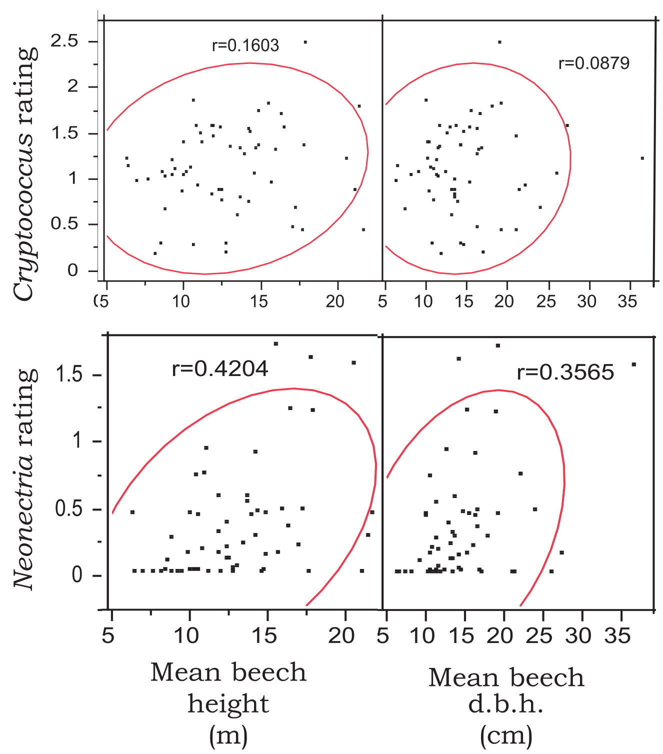

Figure 1.—Correlation matrices and coefficients of mean beech height and d.b.h. with *Cryptococcus* and *Neonectria* ratings, narrower ellipses indicate stronger correlation.

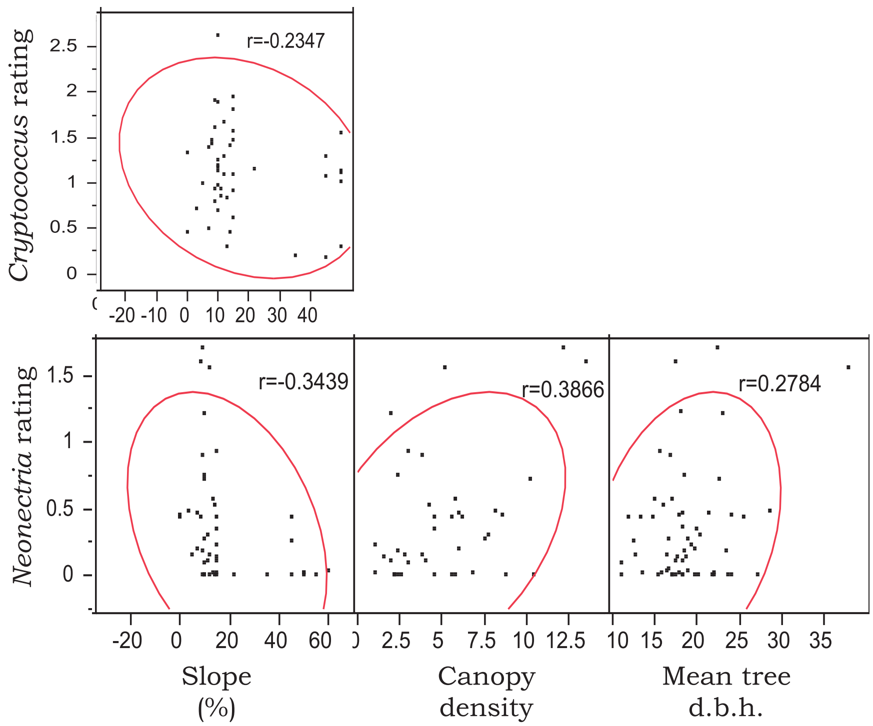

Figure 2.—Correlation matrices and coefficients of slope with *Cryptococcus* ratings and slope, canopy density, and mean tree d.b.h. with *Neonectria* ratings, narrower ellipses indicate stronger correlation.

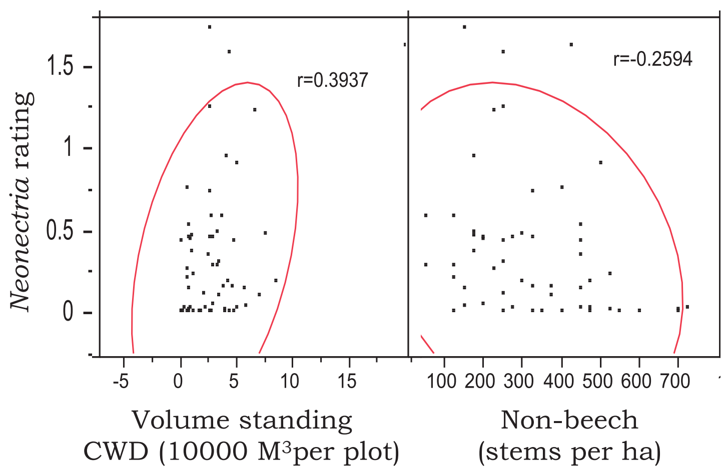

Figure 3.—Correlation matrices and coefficients of non-beech per hectare and volume of standing coarse woody debris with *Neonectria* ratings, narrower ellipses indicate stronger correlation.

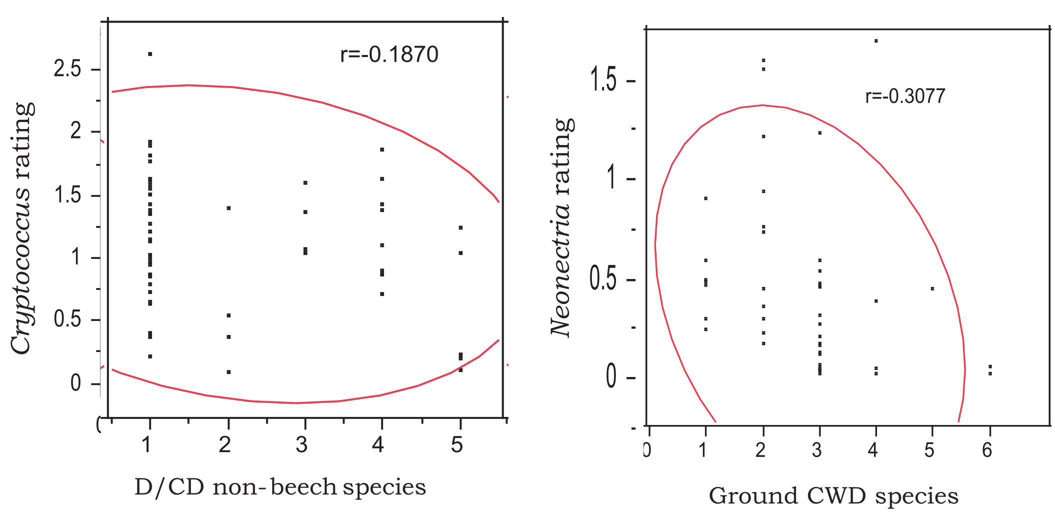

Figure 4.—Correlation matrices and coefficients of dominant and codominant non-beech species composition with *Cryptococcus* ratings and species of ground coarse woody debris with *Neonectria* ratings, narrower ellipses indicate stronger correlation.

Stepwise Regression Analyses

Regression analyses estimated none of the continuous variables analyzed had an effect on scale infestation and only beech height ($p = 0.031$) and slope ($p = 0.033$) were indicated as important to *Neonectria* infection. When these variables were crossed, there was no effect from the interaction ($p = 0.453$). The amount of variability explained by the whole model is small ($r^2 = 0.0633$), but beech height and slope account for essentially all explained variability (combined $r^2 = 0.0633$). Categorical parameters that correlated with scale infestation included species composition of the dominant/codominant canopy strata ($p = 0.034$) and species of ground CWD ($p = 0.008$). These two variables accounted for 70 percent of the variability (combined $r^2 = 0.047$) explained by the model, but again, only a small portion of the variability is explained by the model ($r^2 = 0.067$). Species of ground CWD was the only categorical parameter relevant to *Neonectria* infection ($p < 0.0001$, $r^2 = 0.092$) but only accounted for 11 percent of the variability explained by the model. Precisely which if any categories of these non-numerical parameters (see Table 4) actually influence infestation or infection will be determined in future analysis. When results were validated with additional regression analyses using alternate control settings, canopy species and ground CWD species remained the only correlated variables impacting infestation. Likewise, in analyses to validate results for *Neonectria,* only beech height, slope, and species of ground CWD were consistently estimated as important for infection.

DISCUSSION

About 1-2 percent of American beech are estimated to be genetically resistant to BBD (Koch and Carey 2004). However, 13 percent of beech sampled in this study were free of both scale and *Neonectria* and an overwhelming majority were lightly infested/infected. Predominance of *Neonectria faginata* indicates an extended period of BBD activity (Houston 1994). Also, past mortality with some heavy infection is indicative of an aftermath zone with a long history of BBD (Shigo 1972). The low levels of disease and several decade history of BBD evidenced by CWD and the predominance of *N. faginata* indicated the selected sites were ideal for this study.

This project endeavored to discover ecological factors influencing BBD. Inherited resistance is expressed as gene products or physical attributes of a host that enable it to deter or tolerate pests. Ecological resistance is another mechanism not related to gene expression that defends plants from deleterious effects from insects. It is a noninherited pseudoresistance derived from the effects of environmental conditions more than genetics. Ecological resistance is a temporary condition appearing randomly with little or no relation to coevolution of host and pest and could occur in three ways: host evasion, host escape, and induced resistance (Pedigo and Rice 2006).

Hosts can evade infestation with a reduced exposure time to potential inoculum. Early planting and crop rotations evade damaging insect life cycles. Host escapes seemingly occur by pure chance when susceptible hosts in an affected population remain unaffected. Houston and Valentine (1988) describe severe winter temperatures that negatively affect scale populations and BBD; this may be considered an escape due to climate. Escapes are poorly understood. Induced resistance occurs when the environment or plant ecology exclude insect infestation (Pedigo and Rice 2006). Transient environmental factors such as interspecific competition, changes in nutrient cycles (i.e. fertilization), or plant production of unpalatable substances may temporarily induce resistance (Painter 1951).

For example, bark beetle attacks on pine elicit an ecological (induced) resistance when phenols and terpenes accumulate as a general response to stress induced by the beetles. Beech bark is normally smooth through old age, but severe beech scale attacks can produce necrotic areas that roughen outer bark and inhibit scale establishment (Lonsdale 1983). This could be considered a form of induced resistance.

Most of the environmental characteristics influencing beech scale infestation can be considered factors for induced resistance, but they also can lead to chance escapes. Furthermore, ecological factors may influence *Neonectria* infection much the same way. Correlation matrices (Figs. 1-4) indicated which of the factors sampled in this study may have an effect on BBD causal agents. Regression analysis estimated that dominant/codominant canopy species composition is important to scale infestation. Canopy species composition had the highest correlation with infestation, and the relationship is negative overall, with infestation decreasing under specific canopies. The nature of this relationship is unclear and needs further study. Tree species vary in their efficacy for intercepting or deterring dispersing beech scales. Twery and Patterson (1983) found stands dominated by hemlock contained more diseased beech which contrasts with less infestation in conifer-dominated stands found in this study. However, red spruce (*Picea rubens* Sarg.), not hemlock (*Tsuga* spp.), was the predominant conifer species in study sites. Leak (2006) found that BBD incidence decreased in a stand where yellow birch and paper birch (*Betula papyrifera* Marsh.) were removed as part of a 50-year thinning regime, which corroborates the results reported here. Future analyses will determine which species compositions in the canopy affect scale infestation.

Ground CWD had a very low positive correlation with scale infestation, and regression analysis estimated it to be a relevant factor, but currently it is not clear which categories (Table 4) are important. Scale infestation is affected by nutrient availability in beech bark (Latty et al. 2003, Mize and Lea 1979). Different species of debris decompose and release nutrients at varying rates, and species of CWD would affect recycling of nutrients and possibly nutrient availability in beech bark.

Beech height had the strongest correlation with *Neonectria* infection, and regression analysis indicated it had an impact on infection with taller beech incurring more infection. Beech scale is expected to infest larger diameter beech (Ehrlich 1934, Wainhouse and Deeble 1980). Since scale infestation is a required condition for copious infection, it is logical that larger, taller beech are more susceptible to infection because of their size. Furthermore, taller beech in the canopy are more likely to intercept *Neonectria* inoculum dispersed long distances in upper level wind currents. Correlation matrices indicate *Neonectria* infection decreased as slope increased, a relationship that was supported by regression analysis. Scale and fungal inoculum may be blown over steep slopes by wind currents above the canopy. However, this data contradicts Ehrlich (1934) who reported BBD is more extensive on steep slopes than broad ridge tops, and Houston et al. (1979) reported that scale infestation (and thus perhaps *Neonectria* infection) is generally lesser on gentle slopes.

Ground CWD was the only categorical factor in regression analyses that was important for *Neonectria* infection and it was negatively correlated. Future analyses may clarify which categories of CWD, if any, are most influential. Any effects CWD has on nutrient cycling may influence *Neonectria* as well as scale, thus nutrient availability in beech bark for *Neonectria* fungi may be affected by CWD and its decomposition. This is unlikely, but considering the complex nature of disease, no factor should be completely ruled out as a potential influence on BBD. Other data gathered including advanced regeneration, herbaceous, shrub, and litter layers, and soils will be part of future analyses as will a spatial analysis of disease distribution. Some factors such as bark chemistry are beyond the scope of this study, but would be of interest in future studies.

Given the dynamic nature of BBD, stand characteristics affecting beech scale infestation and *Neonectria* infection interact in a complex way and influence each other as well. American beech has yet to be removed from the landscape in North America, and a full understanding of the beech bark disease complex would help improve management of the disease and avoid the loss of this important ecosystem component. The results reported from this study support the hypothesis that factors other than genetics are influencing disease incidence and severity, but a more thorough investigation over a wider geographic range is needed to definitively identify those ecological factors most influencing the progression of BBD.

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TREATING JAPANESE BARBERRY (*BERBERIS THUNBERGII*) DURING THE DORMANT SEASON

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Abstract.—Japanese barberry (*Berberis thunbergii*) is an invasive shrub that can suppress forest regeneration and increase the risk of exposure to Lyme disease. In 2008, we began a study in central Connecticut to examine the efficacy of treating barberry infestations during the dormant season (October-March). Techniques included basal spray (triclopyr in oil) and clearing saw cutting with a wet-blade application of triclopyr. Dormant season techniques were compared with a glyphosate foliar spray applied in September. Foliar application resulted in a greater reduction of barberry cover (94 percent) compared to basal spray (84 percent) and wet-blade treatments (74 percent). Treatment effectiveness did not differ among months for either of the dormant season techniques. Labor costs did not differ among techniques, averaging 0.13 hours/acre/percent cover (i.e., 3.9 hours for a 1 acre stand with 30 percent barberry abundance). There was a large difference among treatments in amount of herbicide applied with 0.6 (±0.1), 1.4 (±0.4), and 2.8 (±0.4) ounces/acre/percent cover for wet-blade clearing saw, foliar spray, and basal spray applications, respectively. While not as effective as foliar spraying, wet-blade clearing saw and basal spray applications provide an opportunity to control barberry during the dormant season. Wet-blade clearing saw technique can reduce the amount of applied herbicide.

INTRODUCTION

Controlling invasive species is a challenge for forest managers throughout the central hardwood region (Barton et al. 2004, Bowker and Stringer 2011, McGill et al. 2008, Moser et al. 2008) and the greater United States (Miller et al. 2010, Webster et al. 2006). Japanese barberry (*Berberis thunbergii* DC) is classified as an invasive shrub in 20 states and 4 Canadian provinces. It is also established in another 11 states (Natural Resources Conservation Service 2011). Japanese barberry, or barberry hereafter, is primarily an invader of abandoned agricultural fields (DeGasperis and Motzkin 2007, Mosher et al. 2009). Once established in a forest, it can persist at low light levels (Harrington et al. 2004), and due to the lack of a seed bank (D'Appollonio 1997), spreads primarily by layering (DeGasperis and Motzkin 2007, Ehrenfeld 1999).

Invasive species such as barberry affect multiple trophic levels in forested ecosystems. Tree seedlings and native herbaceous plants can be inhibited by dense thickets of barberry and other invasive shrubs (Collier and Vankat 2002, Gorchov and Trisel 2003, Kourtev et al. 1998, Miller and Gorchov 2004). Barberry can directly alter soil biota and chemistry (Ehrenfeld et al. 2001), as well as soil structure and function (Kourtev et al. 2003). In addition, there can be indirect negative effects. Higher earthworm levels have been associated with barberry (Kourtev et al. 1999, Nuzzo et al. 2009) and honeysuckle (*Lonicera* spp.) (Madritch and Lindroth 2009). Increased earthworm populations have been linked to decreased litter layer depth and sequestered carbon (Bohlen et al. 2004), increased phosphorus leaching (Suarez et al. 2003), and salamander population declines (Maerz et al. 2009).

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Invasive shrub infestations can have indirect, adverse effects on human health by functioning as disease foci. Enhanced levels of blacklegged ticks (*Ixodes scapularis* Say) are associated with Japanese barberry infestations (Elias et al. 2006, Williams and Ward 2010). These ticks can transmit the causal agents of several diseases including Lyme disease (*Borrelia burgdorferi* Johnson, Schmid, Hyde, Steigerwalt, and Brenner), anaplasmosis (*Anaplasma phagocytophilum* Theiler), and human babesiosis (*Babesia microti* Franga) (Magnarelli et al. 2006). Higher densities of lone star ticks (*Amblyomma americanum* L.) infected with the causal agents of human ehrlichiosis (*Ehrlichia chaffeensis)* and *E. ewingii* were found in Amur honeysuckle (*Lonicera maackii* [Rupr.] Herder) infestations in Missouri (Allan et al. 2010). Lone star ticks can also transmit the agent of tularemia (*Francisella tularensis*) (Stafford 2007). Increased awareness of the link between invasive shrubs and diseases that affect humans and their pets should increase public support and funding for controlling invasive shrubs throughout the central hardwood region.

Our earlier research has shown that effective barberry control can be accomplished from late spring through early autumn by a variety of chemical (Ward et al. 2010) and nonchemical methods (Ward and Williams 2011). Because of environmental concerns and potential to damage nontarget species when using broadcast herbicide treatments, we developed a two-step process that reduces the amount of herbicide applied. The first step kills aboveground stems by cutting (clearing saw, mowing) or heat (prescribed fire, propane torches). The second step kills the much smaller new sprouts with herbicide (glyphosate, triclopyr) or directed heat using a propane torch. Two studies were established to compare the effectiveness and costs of different treatments to control invasive species (primarily barberry) from October through March (dormant season), extending the results of earlier studies that found that initial control of barberry can be completed from April through September. The specific objectives were: 1) compare wet-blade and basal spray applications during the dormant season, and 2) determine any restrictions to treating during the dormant season.

STUDY AREAS

In September 2008, the Bicentennial Pond study area was established at Schoolhouse Brook Town Park in Mansfield, CT to compare the effectiveness and costs of treatments to control invasive species (primarily barberry) during autumn and early winter. A second study area, Clover Mill, was established in a different section of the park in November 2008 to examine control alternatives during winter. Upper canopies of both study areas were mixed hardwoods (primarily *Quercus* and *Acer* with some *Fraxinus*, *Betula*, and *Carya*). The areas are managed as nature preserves with no sign of earlier harvesting.

METHODS

Design and Measurements

Autumn/Early Winter Treatments

Ten 66 ft by 66 ft subplots were established at Clover Mill for the autumn/early winter treatment study. Subplots were randomly assigned one of five treatments: foliar spray with glyphosate[2] (Prosecutor®, 1 percent solution) in September; wet-blade application with glyphosate (41 percent solution) in October; wet-blade application with triclopyr (Garlon 4®, 61 percent solution) in

[2]Mention of a product or company is for informational purposes only and does not constitute an endorsement by the Connecticut Agricultural Experiment Station.

October; basal bark application with triclopyr (2 percent solution in oil) in October; and basal bark application with triclopyr (2 percent solution in oil) in December. Two replications of each treatment were established at Clover Mill. Treatment details are given below.

Winter Treatments

The winter treatment study at Bicentennial Pond included two blocks of 12 subplots measuring 66 ft by 50 ft. Within each block, subplots were randomly assigned one of six initial treatments: January, February, or March basal bark application with triclopyr (Garlon 4®, 2 percent solution in oil) or January, February, or March wet-blade application with triclopyr (61 percent solution). Next, subplots within each block were randomly assigned one of two follow-up treatments: foliar spray with glyphosate (1 percent solution) or triclopyr (3 percent solution) in late May. This provided two replications of each initial/follow-up treatment combination at Bicentennial Pond.

Measurements

Within each subplot, percent barberry cover was measured utilizing a 5.4 ft^2 (0.25 m^2) sampling instrument which consisted of a 4 by 4 grid with which percent barberry cover was determined by presence/absence within each cell (Ward and Williams 2011). There were 12 sample points within each subplot for each treatment combination for a total of 504 sample points. Cover was sampled in August 2008 (pretreatment) and June 2009 (post-treatment) at Clover Mill, and in November 2008 (pretreatment), May 2009 (before follow-up treatment), and October 2009 (post-treatment) at Bicentennial Pond. The amount of herbicide applied to each subplot was recorded along with treatment time.

Treatments

Herbicide sprays were diluted per label instructions and were applied until wet to target foliage using hand-pressurized backpack sprayers (Solo® Model LCS-2, Newport News, VA). Only foliage or lower stems of invasive species (primarily barberry) were targeted to minimize impact to native species. A dye was added (1 percent solution) to the tank mixes to identify clumps that had not been treated and to prevent spraying clumps more than once. Basal and foliar applications were made with backpack sprayers. Wet-blade treatments were made using an applicator (Sprout-Less®, Madawaska, NB, Canada) that was attached to the bottom of a clearing saw blade (Model FS 450, Stihl®, Inc., Virginia Beach, VA). The applicator was designed to continually apply a thin film of herbicide to the bottom of the clearing saw blade.

Data analysis

Autumn/Early Winter Treatments

A one-factor (initial treatment) analysis of variance (ANOVA) with initial cover as a covariate was used to compare the influence of initial treatments on barberry cover at Clover Mill. All cover values were arcsine transformed prior to analysis (Zar 1974). Tukey's HSD test was used to test for significant differences among initial treatments. Differences were judged significant at $P < 0.05$.

Winter Treatments

A two-factor (application method, month) ANOVA with initial cover as a covariate was used to compare the influence of initial treatments on barberry cover at Bicentennial Pond. All cover

Table 1.—Mean (standard error) initial (August 2008) and final (June 2009) cover (percent) of Japanese barberry and invasives by treatment method at Clover Mill

			Japanese barberry		All invasives	
Application	Month	Herbicide	Aug08	Jun09	Aug08	Jun09
Foliar	September	glyphosate	16 (6) a†	1 (1) b	28 (13) a	8 (4) a
Wet-blade	October	glyphosate	25 (8) a	1 (0) b	40 (20) a	8 (4) a
Wet-blade	October	triclopyr	19 (4) a	8 (0) a	48 (15) a	14 (2) a
Basal spray	October	triclopyr	28 (26) a	3 (3) b	47 (23) a	17 (13) a
Basal spray	December	triclopyr	20 (13) a	9 (4) a	45 (31) a	12 (5) a

†Column values followed by the same letter were not significantly different at P ≤ 0.05.

Table 2.—Mean (standard error) initial (November 2008) and final (October 2009) cover (percent) of Japanese barberry and invasives by treatment method at Bicentennial Pond

	Japanese barberry			All invasives		
	Nov08	Jun09	Oct09	Nov08	Jun09	Oct09
Application method						
Wetblade	66 (5) a†	14 (3) a	1 (0) a	66 (5) a	18 (3) a	2 (0) a
Basal spray	71 (6) a	9 (3) b	1 (0) a	72 (6) a	10 (3) b	2 (1) a
Time of application						
January	65 (8) a	9 (2) a	1 (0) a	66 (8) a	11 (3) a	1 (0) a
February	64 (5) a	16 (4) b	1 (1) a	64 (5) a	21 (5) b	3 (1) a
March	76 (5) a	9 (3) a	1 (0) a	77 (5) a	9 (3) a	1 (0) a

†Column values followed by the same letter were not significantly different at P ≤ 0.05.

values were arcsine transformed prior to analysis (Zar 1974). Tukey's HSD test was used to test for significant differences among initial treatments. Differences were judged significant at P < 0.05.

RESULTS

Autumn/Early Winter Treatments

At Clover Mill, initial barberry cover averaged 22 (±5) percent and total invasive cover averaged 43 (±8) percent (Table 1). While not measured, barberry was 2-3 feet tall prior to treatment. Initial cover of both barberry (F=0.050, df=4, P=0.994) and total invasives (F=0.142, df=4, P=0.959) did not differ among treatments. Triclopyr applications using basal spray in December and wet-blade in October were less effective for controlling barberry than other treatments (F=40.333, df=4, P=0.002), averaging a 57 and 56 percent reduction, respectively. Control of all invasives averaged 72 percent and did not differ among treatments (F=0.360, df=4, P=0.827).

Winter Treatments

At Bicentennial Pond, initial barberry cover averaged 68 (±4) percent and total invasive cover averaged 69 (±4) percent (Table 2). While not measured, barberry was 3-4 feet tall prior to treatment. Initial cover of both barberry and total invasives did not differ between application methods (F=0.539, df=1, P=0.473) or among month of application (F=0.947, df=2, P=0.407). The interaction of application method by month of application was not significant (F=0.223, df=2, P=0.803), and a model without the interaction was used. Although both application methods reduced barberry cover, basal spray was more effective than the wet-blade at 88 vs. 79 percent, respectively (F=12.971, df=1, P=0.002). Effectiveness varied among month of application (F=7.486, df=2, P=0.004). January and March treatments reduced barberry cover more than February treatments at 89, 86, and 74 percent, respectively.

Frequency (the number of points which had at least one barberry or invasive species) averaged 90 percent prior to treatment of both basal spray and wet-blade subplots at Bicentennial Pond. Inevitably, some invasive plants were missed by initial treatments, especially small plants which were easily missed in the dormant, leaf-off conditions of winter and those buried under snow. Frequency of points with barberry averaged 37 and 55 percent after basal spray and wet-blade treatments, respectively.

Follow-up foliar spray applications of both glyphosate and triclopyr in late May after the initial winter treatments were highly effective in reducing barberry cover by 98-99 percent of original cover (Table 2). There was no difference between follow-up herbicides for controlling either barberry (F=0.738, df=1, P=0.401) or total invasive species (F=0.167, df=1, P=0.688). After the follow-up treatments, only 8 percent of points still had live barberry.

Costs

Labor costs (hours/acre) for initial treatments were correlated with pretreatment cover of invasive species, (r^2=0.51, P<0.001), but did not vary among application methods (F=2.005, df=2, P=0.152). Pooling application methods, the estimated time for initial treatment was 1.2 + 0.10 hours/acre/10 percent cover. For example, if the invasive cover was 25 percent, then the treatment time would be 1.2+ 0.1*(25/0.1)=3.7 hours/acre. It should be noted that these estimates do not include time required for travel and preparation time prior to arriving at the field.

The amount of herbicide used varied among application methods (F=25.205, df=2, P<0.001). Basal spraying required approximately 4.4 times more herbicide per acre than wet-blade applications (Fig. 1). Wet-blade application required 6.2 ounces/acre/10 percent cover, while basal and foliar sprays required 27.3 ounces/acre/10 percent cover. Herbicide used (ounces/acre) was correlated with pretreatment cover for both wet-blade (r^2=0.40, chi-square=5.8, df=1, P=0.016) and spray applications (r^2=0.44, chi-square=10.2, df=1, P=0.001).

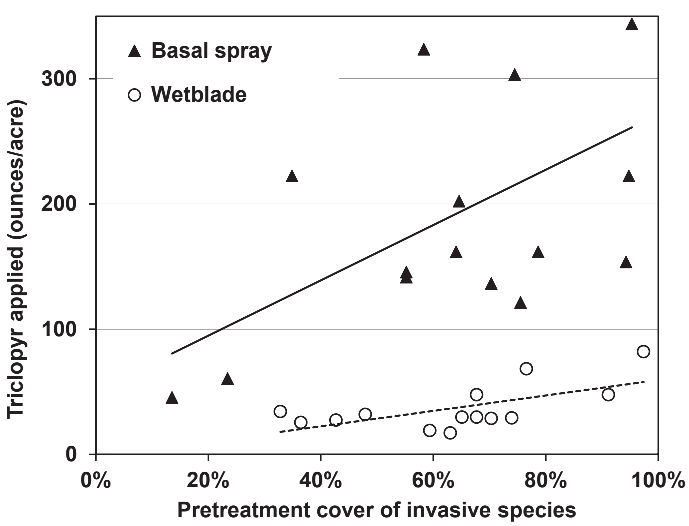

Figure 1.—Amount of herbicide applied (ounces per acre) by pretreatment cover of invasive woody species, primarily Japanese barberry, in central Connecticut.

DISCUSSION

Our results indicated that a program to effectively control Japanese barberry intermingled with other invasive species can be successful when initiated from October through March (Tables 1 and 2). Completing initial control during the dormant season can limit impact to nontarget species, especially herbaceous plants that have lost their leaves.

Combined with earlier work that reported good initial control from April through September (Ward et al. 2010), initial control of barberry can begin throughout the year using a variety of application methods and herbicides, including nonchemical control (Ward and Williams 2011). Therefore, the choice of which application method and herbicide to use as the initial treatment can be tailored to the unique attributes of a site and to the personnel available.

In our study, there was one period when treatment was not as effective. Both wet-blade and basal spray application were less effective in February than in January or March (Table 2). Temperatures were similar during treatment applications in January and February, ranging from 36-40 °F. There was little or no snow on the ground in January and March, but February treatments were applied when there was 6-8 inches of snow on the ground. Because of the snow depth, herbicide application may have been too high on stems to provide for adequate translocation to the root collar and below. In addition, numerous stems offset from vertical were mostly or completely hidden from treatment below the snow. We suggest dormant season treatments should not be attempted if snow depth is more than 1 or 2 inches.

Although effective, we cannot recommend basal spray as a treatment to control barberry for a couple of reasons. First, while basal applications can be an appropriate technique for invasive species with a few large stems (Bowker and Stringer 2011, Lowe et al. 2007, Pergams and Norton 2006), the high number of stems (often 20 or more) in a typical barberry clump (Ward et al. 2009), and the large number of layered stems can require a very high volume of herbicide to be applied on a per acre basis. Our estimate of the amount of herbicide needed (27.3 ounces/acre/10 percent cover) would actually exceed the label maximum (256 ounces per acre) if pretreatment cover exceeded 94 percent. Second, use of an oil (e.g., diesel) as a carrier may be restricted by state/local regulations because of the potential to contaminate groundwater, while commercial basal oils (e.g., methylated seed oils) can be quite expensive on a per acre basis when used in large volumes to treat a species with thousands of stems such as barberry.

Using a clearing saw with a centrifugal herbicide applicator (the wet-blade) was as effective as basal and foliar sprays (Tables 1 and 2) while requiring much less herbicide (Fig. 1), but also has limitations. We noticed that there were strips where all cut stems were dead and other strips where cut stems had new sprouts. We believe that the wet-blade could efficiently transfer herbicide to the blade for 30-45 minutes until the reservoir was about half full. A tank of gas for the clearing saw would last for an hour or more. The period between refilling the gas tank and refilling the wet-blade reservoir was when herbicide was not applied to cut stems. Therefore, until the technology is improved, we recommend pausing at 30 minute intervals to refill the herbicide reservoir and refuel the saw when using wet-blade treatments. Use of the herbicide applicator may be a modification not approved by the manufacture and might invalidate the warranty. In addition, the wet-blade herbicide applicator is quite expensive, costing $490 in 2010.

Other wet-blade studies have had mixed results. Wet-blade applications of diluted triclopyr did not provide effective control of a variety of hardwoods in Pennsylvania (Gover et al. 2002). Mortality of hazelnut (*Corylus cornuta* Marsh.), but not red maple (*Acer rubrum* L.), was increased using wet-blade application of glyphosate in Ontario (Smith et al. 2009). Kirdar and Ertekin (2009) reported wet-blade application of glyphosate provided excellent control of rhododendron (*Rhododendron ponticum* L.) in Turkey.

None of the methods examined in this or earlier studies (Ward and Williams 2011, Ward et al. 2010) provided complete control of invasive species. Eight percent of sample points had live barberry; many were small seedlings that would not survive more than a few years (Ehrenfeld 1999, Ward et al. 2010). While these small plants contribute little to cover, they have the potential to grow and re-infest the site. While it may be unrealistic to achieve complete, multi-year control, a more realistic goal is to provide adequate control to allow the development of desired native herbaceous plants and forest regeneration by periodically retreating the site to maintain invasives at low levels.

Because survival and growth of cut stems did not differ between preleafout and postleafout initial treatments (Ward et al. 2009), we recommend initial treatment during the dormant season when it is easier to see tripping hazards and where barberry is rooted, which would otherwise be hidden by foliage. Cooler temperatures during this period also increase comfort levels of operators wearing thick clothing as protection from barberry spines. Follow-up treatments can be started in late May (Table 2) or delayed until later in summer to minimize over spray (herbicide drift) damage to nontarget native plants (Ward et al. 2010). Biennial monitoring could be used to determine when additional treatments might be required to maintain invasives at levels consistent with management objectives.

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MANAGING AN OAK DECLINE CRISIS IN OAKVILLE, ONTARIO: LESSONS LEARNED

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Abstract.—The town of Oakville, Ontario, is located along the north shore of Lake Ontario between Toronto and Hamilton. In the fall of 2002, significant oak (*Quercus* spp.) mortality was observed at Oakville's Iroquois Shoreline Woods Park, an environmentally significant forest remnant noted for its oak-dominated forests. Investigations suggested that oak decline was responsible for the widespread mortality and that other nearby forest lands were also affected. Oak decline is a disease complex brought on by multiple stresses (e.g., drought, defoliation, high stocking, tree senescence) and secondary pests such as *Armillaria* root rot (*Armillaria gallica*) and twolined chestnut borer (TLCB), *Agrilus bilineatus*. We present a case study that describes the steps that were taken to assess the situation, communicate issues to the public, resolve critical problems (e.g., salvage and hazard reduction), employ trap-tree strategies for TLCB, and develop silvicultural and restoration strategies that include aspects of oak management, regeneration, and prescribed fire. From a municipal forestry perspective, the most important aspects that led to a successful program were accessibility to experts with practical experience and development of effective communication strategies. This is a good case study for municipal foresters who must deal with catastrophic tree mortality in their woodlands similar to that caused by emerald ash borer (*Agrilus planipennis*).

INTRODUCTION

The town of Oakville is located on the northwestern corner of Lake Ontario about 12 miles west of Toronto (Fig. 1). Historically, Oakville has been a leader in managing its trees and urban forests and incorporating forests into the urban environment. In the fall of 2002, John McNeil, town forester and coauthor, became aware of significant oak (*Quercus* spp.) mortality at one of Oakville's high-profile natural parks, Iroquois Shoreline Woods (ISW), noted for its oak-dominated forests (Hanna 1984). After several weeks of assessments and consultations, it was apparent that most of the oaks throughout the park were affected. The park was determined to be unsafe for recreational use and was closed to the public in December 2002. This case study describes the response to this urban forest crisis and has provided some lessons learned that can be helpful to other urban forest managers.

Area municipal and provincial specialists identified the twolined chestnut borer (TLCB), *Agrilus bilineatus*, and *Armillaria* root rot as the causal agents of the oak mortality. Coauthor Peter Williams, a consulting forester and forest biologist with forest health management experience, was retained by Oakville to complete the diagnostic and assessment process, develop a plan for the removal and salvage of hazardous trees, and develop a restoration and management strategy for ISW.

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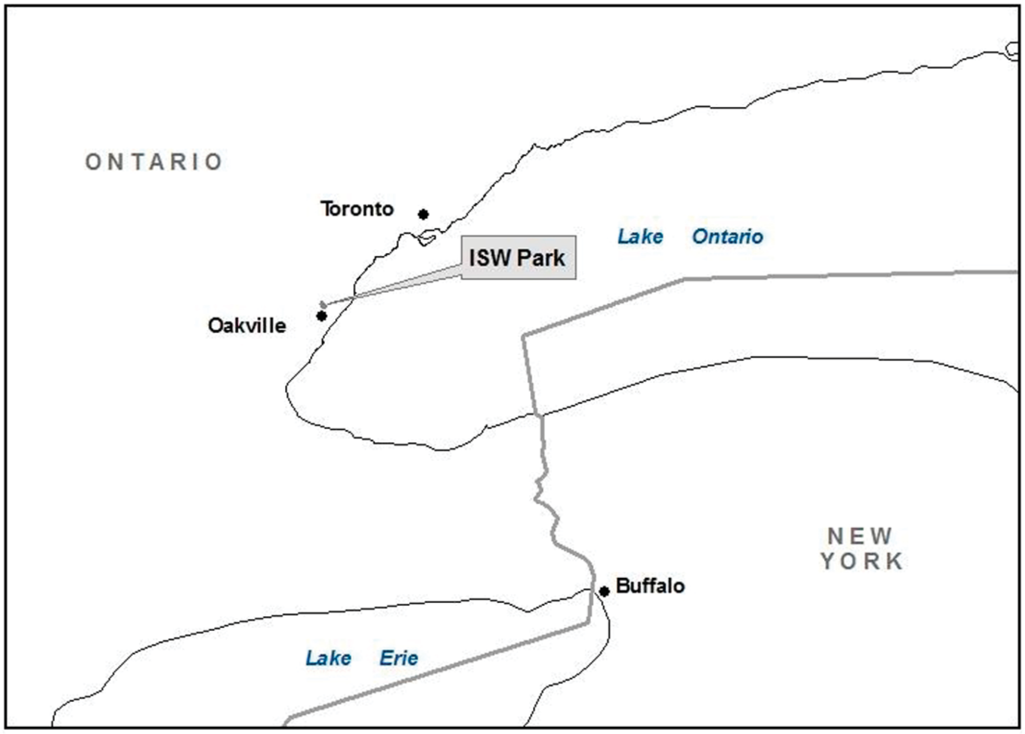

Figure 1.—Location of Oakville, Ontario and Iroquois Shoreline Woods Park.

Williams suggested that ISW forests were exhibiting extreme dieback symptoms that were similar to problems observed on oaks in other area woodlands and previously discussed at oak and mixed hardwood workshops in the United States. Forest managers in southern Ontario primarily use uneven-aged management in the tolerant hardwood forests that are abundant in the region and do not have much experience with even-aged management of oak-dominated forests like those at ISW. Therefore, consultation with U.S. Forest Service researchers experienced with oak ecology and its associated pest complex was recommended. Coauthor Kurt Gottschalk described the dieback as catastrophic oak decline, a stress-related disease complex where over 50 percent of the forest stand is affected. It was later determined that oak comprised about 88 percent of the forest, and approximately 90 percent of the oaks were dead or dying. The need for immediate action required that many steps had to be developed, integrated, and implemented nearly simultaneously in just a few months. These included:

1) Diagnosis of the oak health problem and causal agents and status assessment.
2) Development and implementation of communication strategies.
3) Development and implementation of mitigation strategies.
4) Compilation of lessons learned.

DIAGNOSIS AND ASSESSMENT PROCESS

Concepts of Oak Decline

Oak decline is a complex malady brought on by stress factors followed by successful attack by opportunistic (secondary) pests (Houston 1981; Wargo 1977, 1981; Wargo and Haack 1991). It is a progressive disease where trees can decline in health for several years before dying (Houston 1981, Mannion 1991). Using the decline disease spiral model of Mannion (1991), predisposing factors, inciting factors, and contributing factors represent oak decline events. Common predisposing factors include soil and stand factors, genetics, tree or stand age, and pollution. Common inciting factors include defoliating insects, diseases, frost, drought, and mechanical damage. Common contributing factors include opportunistic insects and diseases. Once a tree is weakened by predisposing and inciting factors, it becomes more susceptible to a variety of insects and pathogens that normally do not affect healthy trees (Mattson and Haack 1987).

Drought and defoliation are the most common stressors that trigger oak decline episodes around the world (Gottschalk and Wargo 1997, Gottschalk et al. 2010). Another important predisposing factor in oak decline is physiological maturity. The cohort senescence theory of decline (Mueller-Dombois 1986) suggests that as trees age and become physiologically mature, their vigor can decline sufficiently to make the entire cohort present in a stand or geographic area susceptible to secondary pests. In southern Ontario, the oak decline episode covered a broad area, and landscape-level defoliation by gypsy moth (*Lymantria dispar*) and successive years of drought were likely inciting factors in this decline episode. High stand density, a cohort of overmature trees, and soil conditions were predisposing factors, and *Armillaria, Hypoxylon* canker, and TLCB were contributing factors to the observed decline.

Background on the twolined chestnut borer

The twolined chestnut borer is a member of the beetle family Buprestidae, which includes primarily species that feed and develop in the inner bark (phloem) and wood (xylem) of their host plants. The TLCB is native to eastern North America, occurring from the Canadian Maritime Provinces of Canada, west to the Rocky Mountains, and south to Florida and Texas (Haack and Acciavatti 1992). The principal hosts of the TLCB are chestnut (*Castanea* spp.) and oak. The TLCB is a secondary pest, commonly attacking trees stressed by drought and defoliation (Dunbar and Stephens 1975; Muzika et al. 2000; Wargo 1977, 1996; Wargo and Haack 1991). The TLCB preferentially attack trees with low root starch levels (Dunn et al. 1987, Haack and Benjamin 1982), a trait common in stressed trees.

Gallery construction by TLCB larvae girdles the tree's conducting tissues, which can result in crown dieback and eventual tree death. In heavily infested portions of the tree, crown foliage will prematurely wilt and turn brown in late summer. Dieback from the crown downward usually occurs over multiple years. As dieback progresses, it is common for epicormic branches to develop along the living portions of the trunk. The TLCB tends to infest stressed trees and little can be done once a tree is infested, especially in forest situations. Therefore, management programs usually focus on prevention by promoting tree and stand vigor by thinning overstocked and overmature stands, reducing defoliation, and avoiding damage to residual trees. In urban areas, managers and landowners can consider mulching, watering, soil aeration, and fertilization programs. Once infestation occurs, local TLCB populations can be reduced through a combination of pesticide applications, use of girdled oaks as trap trees, and early removal and prompt processing of infested trees. Girdled oaks serve as trap trees because TLCB adults are highly attracted to oaks girdled in spring and early summer and will readily lay eggs on such trees (Cote and Allen 1980; Dunn et al. 1986, 1987; Haack and Benjamin 1982).

Background on *Armillaria* Root Rot

Armillaria is the most common root-rotting fungus in the eastern hardwood forest with *Armillaria gallica* being the dominant species in oak-hickory stands (Blodgett and Worrall 1992, Wargo 1993, Worrall 1994). The fungus produces brown to black rhizomorphs (shoestrings) that grow along the surfaces of living or dead roots, outward into soil, and between the bark and wood of roots and trunks of recently-dead trees. Oaks with high starch levels in their roots produce defensive chemicals that prevent invasion by *Armillaria*. However, when oak trees are defoliated the starch is mobilized to sugars, and these chemical changes in the stressed root system predispose the tree to successful *Armillaria* invasion (Wargo 1972, 1984, 1996; Wargo and Haack 1991). *Armillaria* fungi can grow in the cambial region and girdle roots, but usually advances more quickly towards the root tip than the trunk. Given that *Armillaria* species are ubiquitous, there are no real treatments for the disease. However, maintaining tree health can make trees more resistant to infection. Trees infected by Armillaria are often subsequently attacked by TLCB (Dunbar and Stephens 1975, Sinclair et al. 1987, Wargo 1977).

Iroquois Shoreline Woods Park

Iroquois Shoreline Woods Park is located on the upper section of the glacial Lake Iroquois shoreline in Halton County. The site is at the edge of the till plain that had been eroded by the waves of glacial Lake Iroquois and contains relatively-heavy, clay loam till soil (Gillespie et al. 1971). Site index at ISW is 75 ft. at 50 years, or site class 3+ for red oak, which is average site quality for the area (Taylor and Jones 1986). However, site conditions vary depending on the landscape position, with the best site conditions found in the drainages, lower slope positions, and parts of the lower lakebed. The higher level areas had the poorest site conditions due to shallower clayey soils and imperfect to poor drainage, with a tendency to be inundated or saturated in the spring and droughty in the summer.

The local area was settled by Europeans around 1800, and by 1850 it was mostly cleared for agriculture. A large forested area was likely clearcut around 1900 and used for grazing. The ISW is a 70 acre remnant of this larger woodland which contains 55 acres dominated by forest species and 15 acres dominated by hawthorn (*Crataegus* spp.) (Fig. 2). The canopy trees were between 80 and 100 years old. The stand was dominated by red and white oaks with sugar and red maple (*Acer saccharum* and *A. rubrum*), bitternut and shagbark hickory (*Carya cordiformes* and *C. ovata*), beech

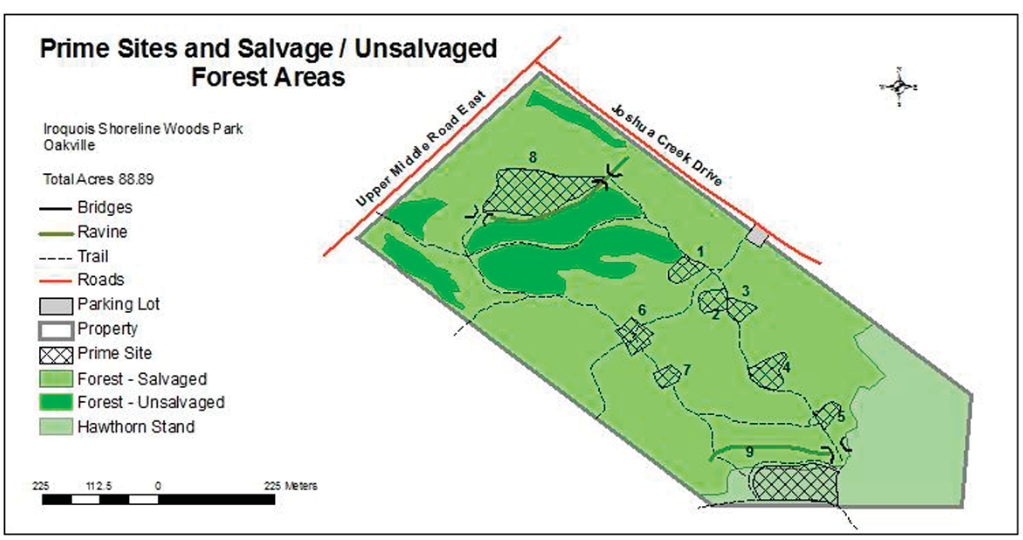

Figure 2 —Map showing the salvaged and unsalvaged forest areas and the prime site locations (numbers 1-9) for oak regeneration within Iroquois Shoreline Woods Park.

(*Fagus grandifolia*), and eastern hophornbeam (*Ostrya virginiana*) making up much of the understory (Perkins 1986). Estimates suggested that the overstory and understory of ISW consisted of 88 percent red oak and 12 percent white oak. The southern part of the property was still undergoing succession from a hawthorn-old field ecosystem to forest in 2003.

The ISW property is bordered by residential subdivisions to the west and north while the south and east are bordered by vacant and commercial land and a major four lane highway. ISW is owned by the Province of Ontario and leased to Oakville until 2033 for use for recreation and conservation purposes. The property includes a trail system used by local residents and the public in general, many of whom frequently express their concerns and interests in the property. A management plan including a description of the history and forests of the property and management objectives and methods was developed for ISW in 1986 (Perkins 1986), but management objectives were never fully implemented.

Oak Decline at ISW

The oak-dominated forest (red, white, and bur oak [*Q. macrocarpa*]) became established under challenging site conditions, and since 1950 there has been no significant forest management activity. As the stand aged, many areas became overstocked and stagnated. Basal area averaged between 135 and 148 ft^2/ac, and oak heights ranged between 65 and 75 ft. Because of the high basal area and age, many oaks had small crowns. Examination of the growth rings on cut trees and stumps confirmed that in general, the trees were growing slowly and were of low vigor.

From 1995 to 1999, the area experienced below average precipitation during four of the five growing seasons. The drought conditions likely exacerbated other unfavourable site conditions (clayey soils and high stand density). Gypsy moth entered Ontario in the mid-1980s and first impacted this area around 1987. Since then, there have been several defoliations from insects, including oak leaf shredder (*Croesia semipurpurana*) in the 1980s and fall cankerworm (*Alsophila pometaria*) in the early 2000s. In 2000, a hard late frost was followed by severe gypsy moth defoliation, resulting in two defoliations in the same growing season.

Inciting factors in this decline episode at the Iroquois Shoreline Woods Park included defoliation by gypsy moth (*Lymantria dispar*), late frost, and successive years of drought. High stand density (overstocked stand), a cohort of overmature low-vigor oak trees, and soil conditions (clayey sites) were predisposing factors. *Armillaria, Hypoxylon* canker, and TLCB were contributing factors to the observed decline. *Armillaria* was associated with many of the dead and dying oaks at ISW as was *Hypoxylon* canker to a lesser extent. TLCB also became an aggressive pest once the problem became epidemic, making it difficult to tell which agent actually killed the most oaks. By January 2003, approximately 96 percent of the oak trees in the understory and 90 percent of the oak trees in the overstory were dead or dying.

COMMUNICATIONS STRATEGY

The use of large-scale forest operations were necessary to respond to the oak decline crisis in the ISW. Due to the importance of ISW as a local park and natural area and because of its location in an urban setting, an effective communications program was necessary to the success of this operation. The important interest groups included municipal administration, municipal council, the general public, and public interest groups. Because oak decline was a poorly-understood disease complex in southern Ontario, the regional forestry and urban forestry communities were important clients as well.

Municipal Staff and Council

The closure of ISW Park for safety reasons in December 2002 placed pressure on the town administration and the town council to rectify the situation quickly. As the nature and scale of the remedies became clear, it was apparent that significant time and resources would be needed and that the required remedial work would be unusual for an urban situation. A report (McNeil 2002, personal communication) was presented to the town council that explained the situation and recommended the closure of the park and a public communications program. The recommendation was approved, and work commenced on developing remedial plans. A silvicultural and regeneration plan for ISW was prepared (Williams 2003, personal communication) that included procedures for removal of hazard trees, harvest and salvage in the majority of the property, and forest restoration plans. Activities and plans were vetted and communicated through the town administration and town council with resounding approval.

Public

The public was advised of the situation and plans through news releases and the local media. However, because of the complexity of the oak decline scenario and the large scale of the problem and planned work, a more direct and personal approach was also used. Two on-site field tours were planned for the public, and written notifications were hand-delivered to residents near ISW describing the situation and inviting those with concerns to contact staff or attend the field tours. Residents were also invited to join a local group, "Friends of ISW", to help with forest restoration efforts such as tree planting.

Public Field Tours

Two public field tours took place in February 2003, just prior to the start of tree removal operations. Because participants would likely represent a range of backgrounds and levels of understanding in forest health and resources, experienced professionals presented basic-level information but were also able to respond to higher-level concerns expressed by some participants.

Five stations (Table 1) were staffed with professional leaders and experienced assistants and were conveniently located in the forest where examples could be demonstrated. The leaders presented the primary information for the station, led discussions, and answered questions. The assistants helped with discussion and questions as appropriate, but also engaged agenda-driven individuals in attendance by drawing them off to the side where they could discuss their concerns individually. Several assistants moved between stations and helped keep the groups synchronized for rotation to the next station.

Table 1.—Topics and staff for the five stations of the public tours

Topic	Staff
Introduction and background	Oakville staff professional forester
Oak decline, *Armillaria* and salvage operations	Professional forester-ecologist
Oak decline and twolined chestnut borer	Forest biologist
Invasive exotic plants and their control	Forest technician
Hazard trees and safety concerns	Arborist and forest technician

The use of highly-qualified station leaders with experience in all aspects of forest ecology and forest health was important so they could answer questions participants had about the project. Providing clear and correct answers to potential questions (e.g., bird habitat) prevented individuals from undermining the credibility of the planning and threatening the project. As expected, a wide variety of citizens including lay persons, council members, and experienced naturalists and ecologists participated. With minor exceptions, the participants accepted that ISW was being managed for forest health rather than income and were comfortable with the knowledge and planning that had gone into the project.

Volunteer Programs and Other Communications

After the park was reopened in August 2003 and restoration efforts were started, programs were implemented to allow volunteers to contribute to tree planting programs and to learn about ISW and other urban forest issues. Volunteer tree planters included members of several interested groups (e.g., Friends of ISW, Oakville Green, and the Oakville Horticultural Society), families and individuals, and school groups.

A prominent and accessible location in ISW was used as the site for events such as Arbor Day celebrations that featured awards by the Mayor's office and announcements such as Oakville's designation as Canada's Forest Capital in 2007, certification as responsibly managed through the Forest Stewardship Council (FSC) Smartwood program, and funding from Green Streets Canada. Events often included presentations by staff or consultants on ISW or other forest health topics, reenactments by First Nations groups, horse logging, and tree-planting events with school groups.

Summary

The pubic communication efforts successfully demonstrated Oakville's interest and support of urban forestry and a commitment to manage its forests for the community. In addition, they provided Oakville with greater credibility in managing forest health crises and contributed to ongoing support and acceptance of forest health management programs, such as aerial spraying for gypsy moth control and emerald ash borer management programs. Similarly, the communication efforts have also resulted in a certain level of expectation by the community that Oakville will be proactive in managing the health of its urban forests.

Professional Education

Consultation with experts in the United States proved critical in elucidating the oak decline scenario and putting together remedial plans. In March 2003, Oakville invited Kurt Gottschalk of the U.S. Forest Service to visit the area, assess the situation, and make management recommendations. Representatives from provincial and local organizations attended the session to become more familiar with oak decline issues. As a result of this visit, Oakville sponsored a workshop to bring together forest health specialists with professional foresters and urban forest managers to develop a better local understanding of oak forest health and decline issues.

Workshop

A workshop entitled "Managing for Oak Decline: A Workshop for Managers of Oak Forests" was held 8-9 July 2003 and sponsored by Oakville with numerous cosponsors. Staff from the U.S. Forest

Service, Williams & Associates, the town of Oakville, Ontario Ministry of Natural Resources, and Conservation Halton developed the workshop and made presentations. The workshop was well received and helped to fill a significant knowledge gap in the region regarding its important oak resources. The success of the workshop was due to the cooperation among local municipalities and agencies to address critical forest management needs that were not being addressed by provincial or federal agencies in Canada. This informal network worked together in subsequent efforts to coordinate gypsy moth and emerald ash borer management programs in southwestern Ontario.

Field Tours

ISW has been used as a stop for a number of forestry professional and educational groups since 2003. In all cases, Oakville has provided experienced personnel to guide the tour and to provide background and advice. These tours have included groups from Canadian Institute of Forestry, the Ontario Professional Foresters Association, and University of Toronto (Urban Forestry Program).

MITIGATION STRATEGIES

Addressing the oak decline crisis in ISW required the development and implementation of mitigation strategies that included silvicultural prescriptions for salvage and regeneration, invasive plant management, and implementation and monitoring.

Silvicultural and Salvage Prescriptions

Silvicultural Strategy

A four-class rating system (Gottschalk and MacFarlane 1993) (Table 2) was used in concert with tree form, crown class, public safety concerns, TLCB signs and symptoms, and TLCB population reduction strategies to guide tree removals. Hazardous trees within one tree length of developed trails and all oaks in condition classes 3 and 4 within 30 ft. of developed trails, parking areas, and property lines, were marked for removal. Trees located 30 to 70 ft from trails, parking areas, or property lines were retained if they posed little potential hazard. These choices were reviewed by forestry technicians, foresters, and certified arborists several times during the process.

Away from the trails, sound dead trees ≥ 6 inches diameter at breast height (d.b.h.) were marked for salvage harvest (Gottschalk 1993). Dead trees with significant wildlife habitat characteristics (e.g., nesting or feeding cavities, or significant decay) that did not threaten trail safety were retained. All Class 3 and Class 2 trees that were heavily infested with TLCB were marked for removal to salvage their value, encourage stump sprouting, and reduce TLCB population by removing them from the area (Gottschalk 1993, Haack and Benjamin 1980). Oaks often regenerate from stump sprouts, but the tree must be alive at the time of cutting to sprout. Oaks with significant decline seldom recover

Table 2.—Oak health and decline rating system used (Gottschalk and MacFarlane 1993)

Class	Class name	Dead branches	Epicormic sprouting	Foliage: Density	Foliage: Size	Foliage: Color
1	Good	<25%	Little/None	Healthy	Normal	Normal
2	Fair	25 to 49%	Some evident	Subnormal	Smaller	Subnormal
3	Poor	>50%	Heavy	Subnormal	Smaller	Chlorotic
4	Dead	100%	n/a	n/a	n/a	n/a

but may sprout from their live stumps. In the interest of maintaining oak in ISW, it was deemed better to cut declining trees to encourage stump sprouting than to let them die completely.

Wildlife Habitat Considerations

ISW is an important stopover for migrating birds in the spring and fall because it is the largest forest patch on the north shore of Lake Ontario between Toronto and Hamilton. Wildlife habitat was an important consideration throughout the planning process. Trees with significant wildlife value (i.e., snags, trees with cavities used for nesting, feeding, or dens, and trees with stick nests used by raptors) were identified and retained if they did not threaten trails. Areas adjacent to these trees were disturbed as little as possible. Tree removal work took place during February and early March during frozen conditions to minimize disturbance to forest soils and associated plant and animal communities, and to reduce the potential impacts on nesting and migratory birds.

Harvest and Salvage Implementation

Salvage harvest operations began in February 2003 and were completed by the end of March 2003. Two cut and skid crews worked full time and harvested approximately 4,000 trees and 250,000 board feet of sawtimber (net scale). A large volume of firewood was also salvaged. About 80 percent of the work was completed with relatively little site disturbance and no damage to the developed trail network. The remaining unharvested area was not salvaged and left to develop naturally except for the removal of hazard trees in the proximity of public use trails. Despite the industrial scale of the harvest in a major urban park surrounded by residential areas and busy roads, there were few public inquiries and many of these regarded firewood availability. The apparent broad public acceptance to this level of activity was attributed to the vigorous communications and frank explanations of the oak decline situation.

Because some hazard trees still remained along the trails, a horse logger was retained to remove these trees so the park could be reopened. These trees were cut and skidded to a landing and sold. Arborists removed dead and hanging branches from the remaining trees near the trails. Damage to the trail from hazard-tree removal was repaired and the park was reopened for public use in June 2003. During 2004 and 2005, new hazard trees and declining oaks were removed as part of the hazard management program or the trap-tree project described below.

TLCB Assessment and Control

Surviving oaks were assessed for general health and evidence of TLCB infestation in June 2003. To reduce the TLCB population, 45 deteriorating Class-2 oaks were girdled at approximately 18 inches above ground to encourage egg-laying by TLCB as part of a trap-tree program as described in Haack and Benjamin (1982). Trap trees would be cut and removed from the site prior to TLCB emergence. In early 2004, additional infested and trap trees were removed from the ISW by skidding with horses to minimize impacts to the forest floor.

Concurrent with trap-tree identification in 2003, non-oaks that were competing with the surviving oaks were also marked for removal to increase the vigor of the surviving oaks (Gottschalk 1993). More vigorous trees are better able to withstand attack by TLCB and *Armillaria*, or are less attractive to these pests (Gottschalk 1993, Haack and Acciavatti 1992, Wargo 1996). Additional declining oaks and hazard trees were identified in August 2004 and removed during the 2004-2005 winter using a tractor and skidding winch.

Oak Regeneration Strategies

Oakville made a commitment to maintain an oak component at ISW, so efforts to maintain the health of surviving oaks in the forest and fostering the development of oak regeneration throughout ISW became a high priority. Two other strategies that were used included enhancing the oak component where appropriate stand conditions existed and using a group selection strategy to develop oak regeneration (Brose et al. 2008). The latter two were implemented using a prime site approach where regeneration efforts were concentrated.

Release of Existing Oak

Surviving oaks were located and released from competition to improve their vigor. Trees competing with surviving oaks were marked for removal so that the residual oaks were free from competition on at least two sides. All trees were felled concurrently with removal of the trap trees during the winter of 2003-2004 and salvaged where operationally convenient. The improved vigor and increased light to the oak crowns should foster production of acorns for development of oak regeneration.

In the hawthorn (*Crataegus*) and buckthorn (*Rhamnus*) dominated compartment at the south end of ISW, some oak and white pine (*Pinus strobus*) seedlings and saplings had colonized and grown above the hawthorn canopy, mostly along the established forest edge. Non-oaks that were competing with these trees were marked and felled. This process was repeated every few years as competing trees encroached on the oaks.

Prime Site Strategy

Because the high financial cost and limited societal acceptance of oak regeneration efforts throughout the whole park was a concern, direct oak regeneration efforts were focused on nine prime sites as indicated in Figure 2. Regenerating oaks in an established forest is often challenging, and this approach allowed the concentration of management activities in a smaller total area, in an effort to improve success, while allowing the remaining forest to develop with minimal human disturbance.

Eight prime sites were established in 2003 and a ninth was added in 2006. Seven sites were located in forest areas where there were few remaining canopy trees, representing a group selection strategy (#1-7 in Fig. 2). These sites ranged in size from 0.2 to 0.5 acres and had nearly all of the slash and any remaining trees and shrubs cut and chipped. The chips were blown into piles and some used to mulch planted seedlings. One of the original sites was in a hawthorn and buckthorn stand (#9 in Fig. 2). As plans were being made for buckthorn control, this site represented a natural succession strategy with elements of a shelterwood.

Once the cutting and chipping was completed, prime sites were planted with red oak seedlings and some white oak, bur oak, white pine, and eastern hemlock (*Tsuga canadensis*) seedlings starting in April 2004. The prime site in the hawthorn/buckthorn area was planted after the buckthorn was treated chemically. Most seedlings were planted by contractors, with some areas reserved for planting by volunteer groups. A high rabbit population in the southern end of the park resulted in up to 100 percent seedling mortality in some areas. Tree wraps were used to protect seedlings and the bases of larger trees after 2004. Tall potted red oak (5 ft.) stock was planted in a number of the prime sites. Oak developed well in some sites but did poorly in others. Oak survival in the prime sites and in the general forest was monitored in permanent sampling plots (Table 3).

Table 3.—Natural and planted oak populations in permanent sampling plots (PSP) in 2003 and 2009 in prime sites and other areas

			2003		2009	
Vegetation	PSPs	Condition	Natural	Planted	Natural	Planted
Forest	9	prime sites	33	944	22	778
Forest	8	salvaged	25	50	25	0
Forest	6	unsalvaged	33	0	33	0
Hawthorn	3		0	267	0	0
Hawthorn	2	prime sites	300	50	300	400

Shelterwood Treatment

The prime site added in 2006 (#8 in Fig. 2) was in an area that was appropriate for a classic shelterwood strategy. Before the decline episode, this site had a very high stand density with approximately 80 percent oak. All of the oak died from decline, but the plot still had a residual canopy of 50 percent to 80 percent canopy closure of residual upper and mid-canopy sugar maple and a dense understory of elderberry (*Sambucus* spp.) that had become established as the oak declined. The site was added to the 2006 prescribed burn plan so that fire could be used as a site preparation treatment to control the elderberry.

Local acorns were collected and planted on site. Additional acorns were planted in greenhouses and nurseries for future planting stock. The direct-seeded acorns did not develop, and the area was planted to seedlings in 2006 after the prescribed burn. The site was planted by volunteers and contractors on several occasions using bareroot tall stock or potted seedlings.

The elderberry and much of the woody debris left from the salvaged oaks were treated with a prescribed burn in 2006, and the site was planted to red oak that spring. Subsequent weak oak-seedling growth was attributed to excess shading from the residual canopy, and a release cut was made in 2008 by removing the mid-canopy maples and utilizing the wood for firewood. The release cut left 40 to 50 percent canopy cover. The site was planted in 2008 with red oak seedlings grown from the 2005 acorn crop.

The oaks planted on this site are growing better than in other parts of the park, likely a result of good site conditions, less browsing from rabbits, and less competition. Although monitoring data has not been analyzed, there is significantly less competition from herbaceous plants and shrubs. A planned 2012 prescribed burn should help reduce the weedy perennial competition and foster oak development.

Prescribed Burning

Prescribed burning is an important tool in oak silviculture for site preparation and competition control. Oak seedlings are adapted to aggressively sprout after low-level fires that kill competing woody and herbaceous vegetation (Brose et al. 2008). It was anticipated that competition would be a problem and that prescribed burning would be an effective control method. A prescribed burn plan (Bruin 2004) and communications plan were prepared for 2004 and scheduled for some of the prime sites in late April 2004.

The 2004 burn was successful, and most competing woody vegetation was killed or damaged by the fire. Despite raking around seedlings to remove fuels, the fire scorched the needles and killed most of the white pine seedlings. Because the soil drainage is impeded at ISW by the clayey soils, wet patches resulted in variable burn coverage on some sites. Visual observations showed that the fire was very effective in reducing first-year buckthorn seedlings that had become established in the hawthorn and buckthorn stand following herbicide treatment in 2003. Garlic mustard (*Alliaria petiolata*) seedlings were also reduced significantly in this area, perhaps because the first year seedlings were susceptible to fire and the tight clay soils. The clayey soil may have kept most of the seed above the mineral soil, and with the leaf litter being the only significant organic layer, much of the seed may have been consumed or killed by the fire.

Prescribed burns have been used four times since 2004 at ISW and a fifth burn is planned for 2012. The burns have been successful in limiting the establishment of woody perennials, fostering oak regeneration, and keeping oak management in the public view. However, patchy wet site conditions that limit fire effectiveness, herbivory by rabbits and considerable amounts of perennial herbaceous competition have caused variable results. The apparently lower rabbit population and partial shade and reduced weed competition seem to be linked to the good results noted in the traditional shelterwood situation.

Monitoring

Permanent sampling plots (PSPs) were installed to monitor forest health conditions at ISW. Overall, 27 PSPs each 0.025-ac in size were installed at ISW. At least one plot was placed in each prime site, and the remaining PSPs were located in representative forest conditions throughout ISW, including the area not salvaged. Data has not been analyzed completely, but preliminary analysis of PSP data showed some reduction in buckthorn seedlings and honeysuckle (*Lonicera*) plants after burning in the hawthorn and buckthorn stand (Table 4). Other preliminary results (Table 3) indicated that between 2003 and 2009 there was no new natural oak regeneration at ISW, and no planted oak seedlings survived outside of the prime sites (Table 3). Planted seedlings did become established in the prime sites following years of planting, prescribed burning, and replanting.

Invasive Plant Management

Populations of common buckthorn (*Rhamnus cathartica*) and garlic mustard were well-established in parts of the hawthorn stand and other forest areas. Glossy buckthorn (*Frangula alnus*) and honeysuckle were scattered throughout the forest in lower numbers. Coltsfoot (*Tussilago farfara*) was present in 2002 or was introduced by horses during salvage operations. It was anticipated that the demise of the oak canopy would provide ideal opportunities for invasive exotic plants to expand their populations. Control programs were developed to limit or reduce the populations of these plants.

Table 4.—Percent ground cover of buckthorn and honeysuckle in burned and unburned permanent sampling plots in 2004 and after prescribed burn in the hawthorn stand in 2005

	Burned plots (3)		Unburned plots (2)	
	2004	2005	2004	2005
	%	%	%	%
Buckthorn	53	44	50	57
Honeysuckle	2	0	4	13

In 2002, the canopy and understory in the hawthorn stand was dominated by buckthorn, and the forest understory in many areas of ISW was infested with common buckthorn. The increasing dominance of buckthorn was causing the decline in the hawthorn stand and interfering with natural succession. All buckthorn over 0.5 inches d.b.h. were treated with a basal bark application of 25 percent tryclopyr in oil, successfully killing most of the buckthorn throughout the park. However, surviving and missed stems required treatment in subsequent years. Continued treatment of smaller stems as they grow will be needed to keep buckthorn populations suppressed.

Garlic mustard heavily infested parts of the forest and the hawthorn stand, and lighter infestations radiated out from the population centers. Site-specific attempts to control garlic mustard have been somewhat effective in limiting infestation growth but were generally not persistent enough to provide effective long-term control. Broadcast spraying of dense patches of garlic mustard with glyphosate and hand-pulling by volunteers and staff was conducted sporadically in prime sites and along infestation fringes to stabilize garlic mustard populations. Prescribed burning dramatically reduced garlic mustard. Efforts to control coltsfoot by spraying in the fall with glyphosate have been successful in limiting its population but insufficient in reducing or eradicating it. Honeysuckle has been treated sporadically along with buckthorn, limiting its population growth.

LESSONS LEARNED

Managing the oak decline crisis in Oakville, Ontario has resulted in six lessons learned that can be shared with other urban forest managers:

1) Reach out to a variety of knowledgeable experts quickly when faced with unfamiliar challenges. Networks of professionals who can help should be fostered through professional groups and by attending technical workshops and conferences. This is critical in an institutional environment of reduced agency budgets and shifting extension and support priorities.
2) Networking with many jurisdictions at different levels helps with problem solving and can help develop programs that may seem beyond the capability of a local or municipal group. In this case, the local network established with area municipalities regarding oak decline facilitated the development of multi-jurisdictional control programs for gypsy moth and communications on strategies to deal with emerald ash borer.
3) It is critical to implement timely, effective, technically-accurate and sensitive communications to interested parties, including staff and administration, politicians, and interest groups. This can lead to general public and institutional support for potentially controversial management activities. The communications efforts for this project helped build municipal and public interest in forest health and acceptance and support of later projects including gypsy moth control programs.
4) Salvage and hazard tree removal activities can be implemented in urban forest situations by a combination of proper management planning and communication of the goals and treatment objectives to interested parties.
5) Prescribed burning has helped reduce the level of woody and perennial competition. The shelterwood approach has also helped to reduce competition, but an appropriate canopy closure must be maintained to both reduce competition and maintain oak vigor.

6) Oak is being successfully established on intensively-managed prime sites, but only with persistent efforts. Although oaks that survived the oak decline episode have revived, partially due to some release treatments, there has been negligible development of natural or planted oak in other parts of the park.

The overall lesson learned is that important natural areas need to be managed to maintain the health of the forest and significant or keystone species. Where significant areas or associations like the oak forest at ISW are successional in nature, a hands-off approach will eventually result in the demise of those associations. Proactively monitoring forest health, maintaining knowledge about the forests and potential health problems, and taking action to keep forests and trees healthy are important. The alternative can be very expensive and unrewarding.

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MANAGING ASH IN FARM WOODLOTS: SOME SUGGESTED PRESCRIPTIONS

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Abstract.—Ash (*Fraxinus* sp.) is an important component of upland sites and is dominant in lowland sites in Southwestern Ontario. While information on emerald ash borer (*Agrilus planipennis*) (EAB) and its signs and symptoms is readily available, there is little on management options that consider EAB affects. This paper was developed from a woodlot tour designed to transfer knowledge to farmers of good forestry and stewardship practices for managing ash. Three generic strategies for certain stand types and four site-specific prescriptions for woodlots in anticipation of EAB infestation are presented. The generic strategies can be considered when developing a prescription for ash-dominant lowlands. They apply to stands infested with EAB and where EAB is expected in 5 to 10 years, or 10 years or more. The site-specific prescriptions are examples that describe applicable issues, strategies, and objectives in more detail. The proportion and size distribution of ash and the number of years anticipated before infestation are important considerations in optimizing ash growth and value and mitigating the impact of EAB on forest structure, value and function. If EAB infestation is expected in 10 years or more, three or four stand entries may be possible to influence the future forest.

INTRODUCTION

Southwestern Ontario is located north of New York and Ohio and east of Michigan. Emerald ash borer (EAB), *Agrilus planipennis,* was first discovered across the river from Detroit, MI in Windsor, Ontario in 2002. Many southern Ontario forests are even-aged or uneven-aged northern hardwood forests that can be managed using uneven-aged silvicultural systems. The Ontario Ministry of Natural Resources (OMNR) and other local institutions primarily support single-tree selection (STS) for managing hardwood and mixed forests. Comprehensive technical support for all systems is provided through the "Silvicultural Guide" (OMNR 2000). Rigorous support for STS and for shelterwoods in white pine (see Table 1 for scientific name for all plants) is provided through the Ontario Tree Marker program.

The forests subject to the greatest changes through attack by EAB are even-aged stands that have colonized former agricultural land, often on poorly-drained or clayey soils. The management of these stands and the types of impacts associated with EAB infestation have received relatively little institutional recognition or support.

This document provides several examples of silvicultural prescriptions that forestry specialists can use to develop alternatives for managing ash in southern Ontario woodlots. These stands have similarities with many forests near the Great Lakes in the United States. It has been reported there is nearly 100 percent mortality of ash over 2.5 cm in diameter at breast height (d.b.h.) (Herms et al. 2009, Knight et al. 2010) It is important to retain some ash in the forest as EAB moves through to provide for diversity, wildlife habitat, and a future seed source. However, the high mortality rate and the loss in

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Table 1.—Common and scientific names for tree and plant species

Common Name	Scientific Name
American basswood	*Tilia americana* L.
American elm	*Ulmus americana* L.
bitternut hickory	*Carya cordiformis* (Wangenh) K. Koch
black cherry	*Prunus serotina* Ehrh.
buckthorn	*Rhamnus* sp. or *Frangula* sp.
bur oak	*Quercus macrocarpa*
green ash	*Fraxinus pennsylvanica* Marsh.
hemlock	*Tsuga canadensis* (L.) Carr.
hophornbeam	*Ostrya virginiana* (Mill.) K. Koch
poplar	*Populus sp.*
soft maple complex	*Acer rubrum L./saccharinum L.*
sugar maple	*Acer saccharum* Marsh.
trembling aspen	*Populus tremuloides* Michx.
white ash	F*raxinus americana* L.
white pine	*Pinus strobus* L.
yellow birch	*Betula alleghaniensis* Britton

wood value when trees die suggest that a prudent land manager would carefully consider management to optimize the value of their ash resource and encourage the forest to become more resilient to EAB and other pests. It is important that forest managers begin considering their alternatives well in advance of actual infestation, especially in stands with over 30 percent ash.

ASH MANAGEMENT STRATEGIES

A stand management strategy should include plans for one or more stand entries that consider the owner's objectives, the likely time frame of infestation, ecological and economic effects of ash harvesting/mortality (current and future stand dynamics), strategies to buffer the effects of impending ash mortality on the stand, the size classes and density of ash present, and existing regeneration. In lowland ash-dominant stands (monocultures), encouraging the establishment and development of other desirable species is critical.

Stand management strategies include several assumptions:

- The number of years before the ash in the stand will be threatened or killed by EAB infestation must be estimated. For example, if EAB has been found 50 km distant, it may be 10 years before that woodlot is affected; if a dense population front was 50 km distant it may be only 5 years.
- The landowner wishes to harvest in their woodlot to optimize the economic value of ash in the woodland and mitigate the impact of the loss of ash on their forest, stand integrity, and productivity.
- Ash is an early- to mid-successional genus and that in ash-dominated stands, a harvest prescription can be implemented which can advance the succession process to develop a woodlot with a greater diversity of mid to shade tolerant tree species.

An ash component made up of vigorous trees should be maintained prior to EAB infestation in order to provide for diversity, habitat, and potential seed sources. Regeneration of desirable non-ash species must be encouraged where it is lacking. If a natural seed source is not available, consider underplanting with appropriate mid-tolerant or shade tolerant species. The short-term economic benefits of harvesting mature, seed-producing ash trees ahead of EAB ash mortality should be weighed against the negative long-term effect on the local gene pool.

This document is not comprehensive and generally applies to the types of stands described in this paper. Information presented here is meant to complement other guidelines and should be read in conjunction with OMNR Forest Health guides "A Landowner's Guide for Woodlots Threatened by Emerald Ash Borer" and "When Invasive Species Threaten Your Woodlot" along with the Regional Forest Health Network pest alert "Emerald Ash Borer (EAB) Information for Woodlot Owners". Examples presented here were applied in Wellington County (Fig. 1) but could also apply in other locales with similar forest types.

Management prescriptions are presented here for three general scenarios:

- Scenario 1: EAB is found in the woodlot.
- Scenario 2: EAB is in the county/region (a quarantine area) or nearby and is expected to infest the stand within 5 to 10 years.
- Scenario 3: EAB may affect the woodlot in more than 10 years.

In addition, prescriptions are provided for the following four actual site-specific stands located in southwestern Ontario (Table 2) where EAB is found nearby and infestation is expected within 5 to 10 years:

- A prescription for an upland tolerant hardwood forest with a higher sugar maple component.
- Three prescriptions for ash-dominant lowland forests of different age/size classes with soft maple as the other major stand component. These are even-aged stands with heavier soils on poorly drained (often seasonally inundated) agricultural sites.

Table 2.—Characteristics of forest stands located in Wellington County, Ontario, Canada

Stand No.	Stand Type	Species Composition	Age (yr)	Initial BA (m^2/ha)	Recommended Residual BA (m^2/ha)
1	Upland tolerant hardwood	30% sugar maple; 30% white ash; 10% bitternut hickory; 30% other (black cherry, hophornbeam, American basswood, poplar, white pine, yellow birch)	95	31	22
2	Lowland ash polewood (10-24 cm)	60% green ash; 20% soft maple; 20% trembling aspen; other (American elm)	~40	34	23±
3	Lowland ash small sawlog (26-36 cm)	50% green ash; 40% soft maple; 10% other (trembling aspen, American elm, sugar maple, black cherry)	50	30	20 ±
4	Lowland ash medium sawlog (38-48 cm)	80% green ash; 20% soft maple; other (American elm)	~70	47	32 ±

Figure 1.—Location map for study area in Wellington County, Ontario, Canada.

GENERALIZED PRESCRIPTIONS FOR STANDS WITH ASH DEPENDING ON EXPECTED TIME TO INFESTATION

Scenario 1. General Prescription Where EAB is Found in Woodlot

In stands where the ash component is greater than 30 percent stand density, it is generally recommended to salvage most saw log trees and as much fuelwood as possible to encourage the development of other species and maintain stand integrity. Recommendations will also depend on the ability of the owner or contractors to harvest smaller fuelwood trees. While it is clear that for the foreseeable future, EAB will kill most ash as it moves through the long-term future is not clear. Wood movement to less infested areas should be discouraged.

It is reasonable to assume that most or all ash that remains in a woodlot infested with EAB will be killed. Thus, it is important to retain a proportion of healthy small to medium saw log and polewood ash that will provide growing stock, seed sources, and wildlife habitat that will ease the transition of a stand to one without a significant ash component. These choices depend somewhat on the owner's objectives, stand characteristics, and the ability of the owner or contractors to harvest/salvage trees. If the owner uses fuelwood, sells it, or has other ways to salvage, the options are much greater, particularly with stands dominated by smaller ash.

In general, it is recommended to harvest/salvage larger ash (>48 cm d.b.h.) if they can be harvested without excess site disturbance or damage to non-ash species. Total basal area reduction should generally not exceed 40 percent. This can usually be achieved by harvesting the larger ash trees while thinning those of poorest health across the diameter classes and leaving a reasonable percentage of small to medium-sized ash (30 to 48 cm d.b.h.).

In ash-dominant stands, this will still leave much ash that will likely be killed by EAB. These can be salvaged for several years after mortality and used as fuel or low-grade lumber. In the meantime, their presence will provide a shelterwood effect to foster the development of residual trees and regeneration.

If the stand is a quality mixed stand, retain smaller but vigorous ash that are inconvenient to access to minimize damage to residual trees. The retained ash will likely die as EAB moves through, self-thinning and providing wildlife habitat without damaging residuals. If they survive, they may help replenish the stand.

Scenario 2. General Prescription Where EAB is in the County/Region (a Quarantine Area) or Nearby with Expected Infestation in 5 to 10 Years

The variety of stand types, species composition, stocking, and past management only allow for general guidelines. Examples of specific situations are presented later in this paper. Because the stand is expected to be affected by EAB within the next 10 years, mark as much ash as feasible while maintaining stand integrity using two stand entries. In the first entry, ash should be marked to encourage the development of non-ash stand components and capture the value before the trees die. Retain vigorous, good-quality medium-sized trees to optimize their growth prior to infestation. This also provides the opportunity to have healthy trees going into the infestation and a choice whether to salvage them or leave them as a seed source for regeneration. A general reduction in the density of larger ash will capture their value and may help to reduce the EAB population in the stand.

Where ash makes up less than 30 percent of the stand density, a single entry using normal procedures could be used. In ash-dominant stands, this will still leave much ash that will likely be killed by EAB. These can be salvaged for several years after mortality and used as fuel or low-grade lumber. In the meantime, their presence will provide a shelterwood effect to foster the development of residual trees and regeneration. Where regeneration of non-ash species is lacking and there is limited local seed source, consider underplanting with appropriate species.

Where ash is dominant or is greater than 30 percent basal area (BA), the number of years before EAB infests the stand is an important consideration that determines the number of entries possible before mortality. It is important to consider that smaller trees can be salvaged for fuelwood up to 4 or 5 years after mortality. This provides for an additional stand entry to salvage ash trees that have died during or after the infestation.

Scenario 3: General Prescription Where EAB May Affect the Woodlot in More Than 10 Years

If it is anticipated that an ash-dominated stand will not be infested for 10 years or more, there may be time for three or four stand entries spaced 5 to 10 years apart. This will help optimize the value and growth of ash before infestation and moderate the impact of EAB on the forest. The sooner efforts begin, the more the development of species other than ash can be encouraged while still retaining healthy ash, should genetics or new control methods prevail over the EAB.

The first entry should be to reduce unacceptable growing stock (UGS) of ash and other species by harvesting with an improvement thinning in all diameter classes. Retained ash trees should be vigorous trees with good, straight stems that will either accumulate significant volume before EAB affects the stand or will move up a product/grade class to optimize value growth. For example, a 14 inch diameter tree could grow to 16 inches in 10 years, moving from a fuelwood or pallet tree to a Grade 1 butt log. When comparing trees of similar quality, ash should be marked to release non-ash species.

With two entries before infestation, a generalized prescription for an ash-dominant stand would be to reduce basal area by an average of 30 percent at the first entry. Diseased trees, trees that are at high risk to fail, trees with height and grade limitations, and dense patches should be marked for harvest and to release better quality trees of all species.

Some vigorous dominant or codominant ash should be retained and released to encourage their value/volume growth before the next stand entry. Ash should be thinned heavily where soft maple or other non-ash advanced regeneration is in the understory.

In ash-dominant stands, this will still leave much ash that will likely be killed by EAB. These can be salvaged for several years after mortality and used as fuel or low-grade lumber. In the meantime, their presence will provide a shelterwood effect to foster the development of residual trees and regeneration. Where regeneration of non-ash species is lacking and there is limited local seed source, consider underplanting with appropriate species.

Where there is soft maple or non-ash regeneration and no larger trees to be marked, smaller ash should be thinned/marked to improve the vigor and development of the other species. Smaller ash which are below marketable size should be marked where operationally convenient (i.e., near trees marked for other reasons, to provide access to other trees, or to encourage the development of other species). Most of the remaining ash should be healthy trees with potential to grow into saw log sizes by the next stand entry (5 to 10 years), just before or when the stand becomes infested. Trees with significant wildlife value (e.g., cavity trees) should be retained.

FOUR SITE-SPECIFIC PRESCRIPTIONS WHERE ASH IS FOUND IN THE LOCAL AREA

Stand 1. Upland Tolerant Hardwood

Stand Description

This upland forest site (see Tables 2 and 3 and Fig. 2 for characteristics) was located on a drainage sideslope between a field to the north and a wetland to the south. It was made up of two even-aged patches. The main part of the stand became established after clearcutting in the early 1900s and subsequent pasturing. A strip along the field edge was likely open pasture until the 1950s when grazing was discontinued. The stand had an improvement cut during the 1980s.

The stand was mostly made up of very good quality, healthy trees, particularly sugar maple. However, the stand was overstocked, and trees were dying because of high density. To maintain tree vigour and reduce the impact of EAB (likely to affect the stand within 10 years), it was recommended to conduct a crown thinning, primarily removing ash with a lighter improvement cut for the other species.

Table 3.—Basal area (m^2/ha) distribution for four forest stands located in Wellington County, Ontario, Canada

Tree Size Classes (cm)	10-24	26-36	38-48	50-59	Total
Recommended residual basal area for STS[a]	4	5	6	5	20
Upland tolerant hardwood	6	16	7 (1)[b]	3	32
Lowland ash polewood (10-24 cm)	21	10 (6)	4 (2)		35
Lowland ash small saw log (26-36 cm)	8	12 (5)	9 (4)	4	33
Lowland ash medium saw log (38-48 cm)	8	18 (8)	15	4 (2)	45

[a]STS = Single Tree Selection system
[b]Number in parenthesis represent unacceptable growing stock (USG) in each size-class category

Landowner Objectives

Maintain a healthy woodlot and provide income using good forestry practices.

Silvicultural Prescription

The single tree selection system should be used in this stand. The stand should be thinned to harvest/salvage larger ash, to release high quality residuals of non-ash species, to provide income, and to improve growing conditions for the remaining residuals and younger trees. Large saw log ash over 48 cm, diseased trees, trees that are high risk to fail, trees with height and grade limitations, and dense patches should be marked for harvest to release better quality trees. Smaller ash, particularly those less than 30 cm, should be marked where operationally convenient (i.e., near trees marked for other reasons, to provide access to other trees, or to encourage the development of other species). Individual/clumps of important trees (e.g., high quality maple, hemlock, yellow birch) should be released using a crop-tree strategy on at least one side. Basal area should be reduced by an average of 30 percent, leaving an average residual basal area of 22 m^2/ha. Marking should be done to reduce potential felling damage and remove UGS to improve the health, value, and growth of the residual stand. Structurally unsound and dying/dead trees that may fall on the trail should be marked for cutting. Trees with wildlife values such as stick nest, cavity trees, and hemlock, should be retained.

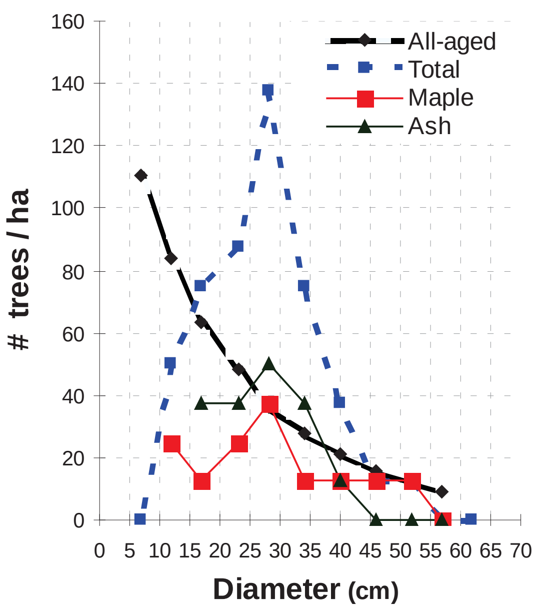

Figure 2.—Stand structure chart for Stand 1, typical upland tolerant hardwood stand.

This harvest is not likely to result in new seedling establishment because of the high residual stand density. It is recommended that the woodlot be assessed after it stabilizes in 5 years or when affected by EAB to assess stand response and develop supplementary recommendations. Otherwise, the next stand entry could be within 8 to 12 years.

Cautions

Avoid harvesting from late March through June to minimize damage to valuable regeneration and disturbing wildlife. The felling of all marked trees within 30 feet of the trail and others that may fall on the trail should be required.

Stand 2. Lowland Ash Polewood (10-24 cm d.b.h.)

Stand Description

The stand was an even-aged swamp (see Tables 2 and 3 and Fig. 3 for characteristics), seasonally inundated and traversed by an open drain. The western parts of the stand were likely open pasture in the 1950s and the rest of the stand was heavily pastured and likely diameter-limit cut in the late 1990s. It was a single-aged stand dominated by green ash that were rapidly becoming suppressed. The poplar was declining. There was a reasonable amount of soft maple in the overstory, and sapling/seedling regeneration was present. The soft maple was generally good-quality.

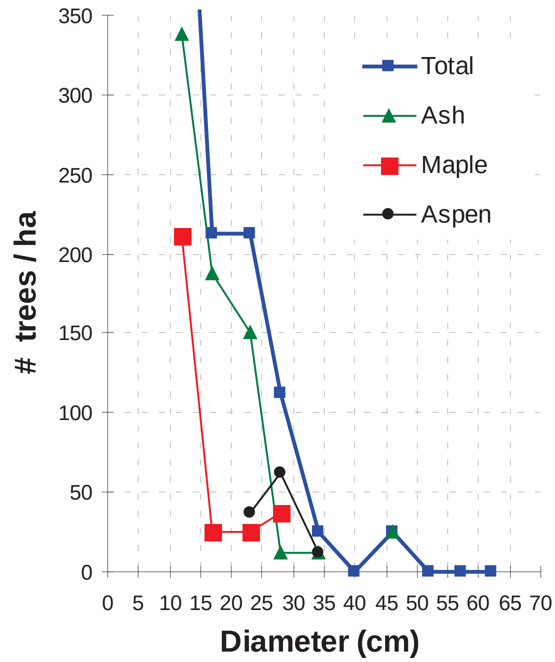

Figure 3.—Stand structure chart for Stand 2, lowland ash polewood stand.

Landowner Objectives

Maintain a healthy woodlot, improve quality and diversity of the stand, and salvage value prior to emerald ash borer infestation while encouraging development of other species.

Silvicultural Prescription

Using a shelterwood approach, the stand should be thinned heavily (30 percent or more), reducing the ash component and encouraging soft maple and other species, and regeneration. As the stand will likely be affected by EAB within the next 10 years, as much ash as feasible should be marked to reduce the future impact of this invasive pest. The ash component should be reduced by retaining the most vigorous individuals while removing UGS and intermediate/suppressed ash. Vigorous dominant or codominant trees between 30 and 48 cm should be retained and released to encourage their growth before the next stand entry. Larger soft maple should be released on at least one side by marking adjoining ash. Ash should be thinned heavily where soft maple regeneration is in the understory. Between 30 and 40 percent basal area should be marked, leaving a residual of approximately 23 m^2/ha. Most of the remaining ash should be healthy trees with the potential to grow into saw log sizes by the next stand entry (10 years). Diseased trees, trees that are high risk to fail, trees with height and grade limitations, and dense patches should be marked. Trees with wildlife values such as stick nest and cavity trees should be retained.

Assuming that this harvest is completed expeditiously, the stand should be assessed for a follow-up thinning in 2017 or sooner if the stand is being attacked by EAB. Regeneration is expected to be soft maple, ash, and aspen. The landowner should consider underplanting with appropriate species (e.g., bur oak, soft maple, yellow birch.)

Cautions

To avoid rutting, the harvest should be conducted in dryer or frozen conditions.

Stand 3. Lowland Ash Small Saw Log (26-36 cm d.b.h.)

Stand Description

The stand was an even-aged swamp (see Tables 2 and 3 and Fig. 4 for characteristics), seasonally inundated and located in a swale between two fields attached to a larger wetland to the north. The stand was likely pastured heavily until the 1960s and left to regenerate. It was a single-aged stand dominated by green ash. The stand was marked using good forestry practices in 2003, and poorly-formed saw log trees were harvested. There were many poor quality ash (firewood-sized and borderline saw logs) and patchy regeneration of ash and soft maple. Many codominant trees around 40 cm were present, with some larger dominants and many saplings. Poplar was present on the east side but was not included in the current assessment. Many of the ash had significant defects and a number were falling over. The soft maple regeneration is generally good and should be encouraged. There is a dense buckthorn understory in places.

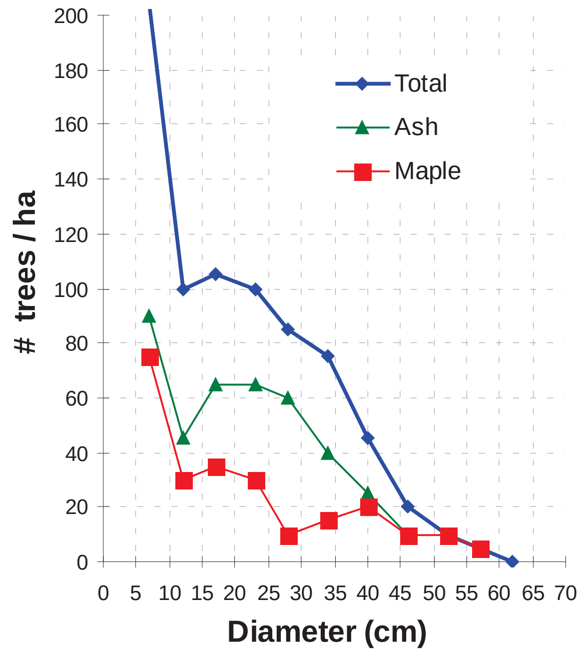

Figure 4.—Stand structure chart for Stand 3, lowland ash small saw log stand.

Landowner Objectives

Maintain a healthy woodlot, improve quality and diversity of the stand, and provide economic return using good forestry practices.

Silvicultural Prescription

The prescription is for the second entry in a three-entry shelterwood approach. The stand should be thinned heavily (30 percent), reducing the ash component and encouraging soft maple, other species, and regeneration. As the stand will likely be affected by EAB within the next 10 years, as much ash as feasible should be marked to reduce the future impact of EAB. The ash component should be reduced by harvesting larger trees (48 cm or greater), UGS, and intermediate/suppressed ash. Most of the remaining ash should be healthy trees with the potential to grow into saw log sizes by the next stand entry in10 years. Intermediate crown class and larger soft maple should be released on at least one side by marking adjoining ash. An average of 30 percent basal area should be marked, leaving a residual of approximately 20 m^2/ha. Diseased trees, trees that are high risk to fail, trees with height and grade limitations, and dense patches should be marked. Trees with wildlife values such as stick nest and cavity trees should be retained.

Assuming that this harvest is completed expeditiously, the stand should be assessed for a follow-up harvest in 2017 or sooner if the stand is being attacked by EAB. Regeneration is expected to be soft maple, ash, aspen and perhaps cherry. The landowner should consider buckthorn control to aid in the establishment of more desirable vegetation.

Cautions

Care should be taken to avoid damaging high quality residual stems, and the harvest should take place during dryer or frozen conditions to avoid rutting.

Stand 4. Lowland Ash Medium Saw Log (28-48 cm d.b.h.)

Stand Description

The stand was an even-aged swamp (see Tables 2 and 3 and Fig. 5 for characteristics), located in a swale between a field and a road. This seasonally inundated stand was connected by culverts to a larger swamp to the south. The stand was likely clearcut in the early 1900s and likely pastured heavily through the 1950s. It was an excellent single-aged stand dominated by green ash. The site quality is exceptional for green ash and soft maple, with an estimated 30 to 35-m canopy height. It does not appear that there has been any historic harvesting and the last stand disturbance was likely in the 1970s when the elm died.

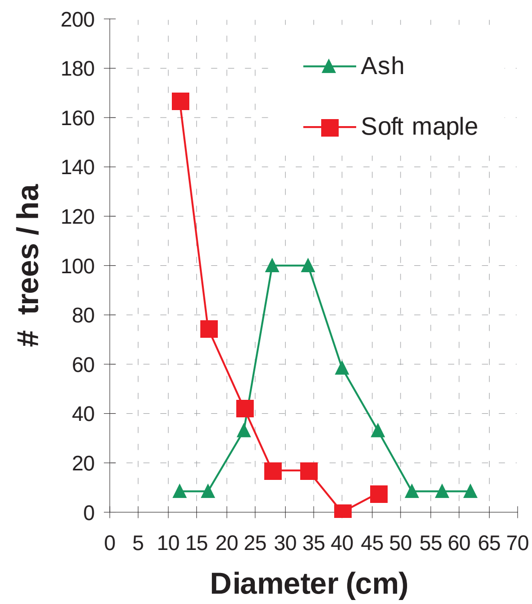

Figure 5.—Stand structure chart for Stand 4, lowland ash medium saw log stand.

Many of the trees have stagnated because of the high stand density. Because of the high proportion of ash, the excessive stocking and resulting lack of stem taper, it is clear that this stand will be devastated when emerald ash borer affects the area in an estimated 10 years. There are scattered soft maple in dominant to intermediate crown positions and scattered soft maple saplings and seedlings.

Landowner Objectives

Maintain a healthy woodlot, optimize economic returns prior to ash borer infestation and encourage the development of other species.

Silvicultural Prescription

This is the first entry in a three-entry shelterwood approach. It is recommended that two more stand entries be made within the next 10 years. The first entry should reduce the stand density by about 30 percent, with a second entry in approximately 7 years. Details of the second entry would be developed based on stand conditions and proximity of EAB infestations at that time. The first entry should harvest a significant saw log volume/acre, encourage the development of species other than ash, and retain individual ash that are increasing in volume and value.

To achieve the basal area reduction, UGS ash over 48 cm should be marked, any ash should be marked to release soft maple or other non-ash species of any size. Where soft maple or non-ash regeneration is present and there are no larger trees to be marked, smaller ash should be thinned/marked to improve the vigour and development of the other species.

To help maintain stand integrity, dominant ash with bigger crowns can be retained, and low-vigor trees should be marked. The healthy dominant trees will continue to increase in volume and help hold the stand together until the next entry). Unmerchantable UGS or UGS with large crowns may also be left to help maintain stand integrity and allow for other trees to be salvaged during this entry. Trees with significant wildlife value (e.g., cavity trees) should be retained.

Soft maple present as advanced regeneration is expected to become the main species. To improve stand diversity, bur oak, yellow birch, and hemlock could be planted in larger openings where there is no advanced regeneration.

Cautions

The stand should be cut in dry or frozen conditions to avoid rutting, although this stand is not as wet as other swamps in the area and a larger window for harvesting is present.

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FOREST SOILS AND HYDROLOGY

SEDIMENT ASSOCIATED WITH FOREST OPERATIONS IN THE PIEDMONT REGION

Kristopher R. Brown, W. Michael Aust, and Kevin J. McGuire[1]

Abstract.—Reduced-impact forestry uses best management practices (BMPs) during operations to minimize soil erosion and sediment delivery to streams and to maintain or improve site productivity. However, the efficacy of specific types of BMP implementation is not widely documented. This review synthesizes recent research that investigated contemporary BMP implementation and effectiveness in water quality protection associated with the following forest management operations: forest roads and skid trails, streamside management zones, harvesting, site preparation, and stream crossings. The review concentrates on studies conducted in the Piedmont region of the eastern United States and facilitates integration and comparison with forestry BMP effectiveness research from the western United States. General results indicate that the most serious water quality issues are associated with bare soil conditions that are hydrologically connected to streams by roads, skid trails, or concentrated flows. Future research should determine sediment delivery ratios for forest road and skid trail approaches to stream crossings in order to develop and implement management strategies for minimizing sediment that has the highest probability of reaching the stream.

INTRODUCTION

Sediment is one of the most frequently cited water quality concerns associated with forestry operations (Grace 2002, Riekerk et al. 1989, Stuart and Edwards 2006) and is consistently ranked among the top 10 causes of river and stream impairment in the United States (U.S. Environmental Protection Agency 2003). Streams flowing through forested land generally have lower sediment concentrations relative to agricultural or urban areas, owing largely to the presence of the forest floor. The forest floor is composed of leaf litter and woody debris, which prevent soil erosion in a variety of ways. The forest floor covers bare soil and prevents sediment detachment from rainfall droplets. The forest litter layer, humus, and mineral soil have high infiltration capacities that are rarely exceeded, even by intense rain events. When surface runoff does occur, litter decreases the velocity of overland flow and acts to trap sediment.

Typical forest operations include access road construction and maintenance, installation of water control structures and stream crossings, harvesting and thinning, skidding, building log decks, fireline construction, burning, and site preparation. Each of these operations increases the percentage of bare soil within a watershed, thus increasing soil erosion and the potential for sediment delivery to streams. Forest cover removal generally results in short-lived streamflow increases as a result of decreased evapotranspiration (McGuire and Likens 2011). Increases in stormflow volumes and peakflows can accelerate within-channel erosion.

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Forest operations commonly occur within the drainage areas of zero-, first-, and second-order streams. These headwater streams may be ephemeral, intermittent, or perennial. Headwater streams compose more than two-thirds of the cumulative drainage length of river basins and link riparian and upland habitats to downstream ecosystems by providing streamflow, physical habitat, allochthonous organic material, and aquatic life (Benda et al. 2005, Freeman et al. 2007). Therefore, headwaters can govern downstream hydrologic conditions and water quality on a regional scale. For example, Dodds and Oakes (2008) stress the importance of riparian buffers in headwater reaches for the protection of downstream aquatic ecosystems.

Reduced-impact forestry uses best management practices (BMPs), which have proven to be generally effective in minimizing sediment inputs to streams (Aust and Blinn 2004, Wang and Goff 2008, Ward and Jackson 2004). However, BMP implementation does not eliminate sediment delivery to streams altogether. For example, in a review of three paired watershed studies in the eastern United States, Edwards and Williard (2010) calculated that BMP implementation reduced sediment by 53 to 94 percent. Often, BMP failures that contribute sediment to streams are non-uniformly distributed and occupy relatively small proportions of the total forest operational area. Rivenbark and Jackson (2004) estimated that approximately 0.33 to 0.4 percent of industrial forest land in the southeastern portion of the eastern United States' Piedmont physiographic province is contributing to streamside management zone (SMZ) failures at any given time.

Much work has yet to be done to understand both the spatial distribution of BMP failures within a watershed or operational area and the causes of BMP failures. For example, slope steepness, surface runoff contributing area, topographical feature type (e.g., gullies and swales), bare soil percentage, and their interactions have been used to aid in the characterization of sediment problem areas (Rivenbark and Jackson 2004).

Evaluation of reduced-impact forestry practices to minimize soil erosion and sediment delivery to streams is particularly relevant for the Piedmont. For more than a century before the 1930s, poor agricultural practices associated with row crop agriculture of corn, cotton, and tobacco caused extensive soil loss, gully formation, and aggradation of stream channels across the Piedmont, particularly in the southern states. Trimble (1985) describes an era of "land rotation," whereby exhausted farmland was abandoned and left to regrow, while forested land was cleared for new farms. This practice resulted in a highly eroded landscape, with sediment-laden stream channels and valley bottoms. Soil loss across the Piedmont has been estimated to be 60 cm or more (Trimble 1985). Although this region is now mostly forested, Piedmont streams continue to export these legacy sediments; this ongoing process confounds the quantification of contemporary land use effects on stream sedimentation (Jackson et al. 2005).

In addition, suspended sediment production from Piedmont forestry operations is high in comparison to mountainous and coastal plain sites of the southeastern United States because of the interaction between site preparation intensity and topographic relief (Riekerk et al. 1989) and clay-rich soils. Industrial forest operations are ubiquitous throughout the Piedmont. The anticipated increase in demand in the South for forest products (Anderson and Lockaby 2011) heightens the importance of understanding how well reduced-impact forestry practices perform in protecting stream water quality under various scenarios that may include increased stand entry, shorter rotations, and higher overall production over fewer forested areas.

Unlike well-known research sites in the Northeast, such as Coweeta (North Carolina), Hubbard Brook (New Hampshire), Fernow (West Virginia), and Leading Ridge (Pennsylvania) (Ice and Stednick 2004), the Piedmont physiographic province lacks a cohesive research unit. However, many recent studies have been conducted in this region regarding the effects of contemporary reduced-impact industrial forest operations on soil erosion and sediment delivery to streams. The objectives of this review are to consolidate and organize study findings by forest operation, including recent unpublished graduate theses; evaluate BMP performance for specific operations; and identify future research needs to minimize sediment delivery to streams.

FOREST OPERATIONS AND SEDIMENT IN THE PIEDMONT

Harvesting and Site Preparation

Timber Harvesting

Generally, harvesting itself does not substantially increase soil erosion. However, skid trails, log decks, and roads commonly cover 2 to 10 percent of logged sites (Kochenderfer 1977) and represent the most significant threat to water quality from forest operations due to an increase in erosion potential resulting from bare soil exposure, compaction, and increased surface runoff. Nutter and Douglass (1978) defined "soil-loss tolerance" for traditional agriculture (e.g., row crop agriculture) as the maximum average annual rate of soil erosion that permits a high level of productivity to be sustained economically and indefinitely. Soil-loss tolerance ranges from 4.4 to 11.2 Mg/ha for intensively managed (fertilized and site prepared), "good" agricultural soils in the Piedmont. The authors contended that most harvest methods would not exceed the soil-loss tolerance for agricultural soils and recommended that following harvest, there should be no site preparation that would expose additional mineral soil on slopes greater than 15 percent. This recommendation indicates an awareness of the potential for high rates of soil loss owing to the interaction between slope steepness and intensive site preparation practices that expose bare soil.

Pye and Vitousek (1985) estimated soil erosion rates resulting from clearcut harvest of 22-yr-old loblolly pine (*Pinus taeda*), followed by site preparation in the Piedmont of North Carolina. The study location was characterized by gentle slopes (0 to 10 percent) and clayey, kaolinitic, thermic Typic Hapludult soils. Three blocks (5 ha each) were clearcut, with half of each block either stem-only or whole-tree harvested. One half of each harvest treatment was drum chopped. The other half of each harvest treatment was sheared and windrowed, and the inter-windrow areas were disked. Most of the windrows were burned, but burning was unsuccessful for the drum-chopped areas. Finally, the four resultant treatment combinations were halved. Herbicide was applied to one half and not to the other. The split-split plot experimental design was replicated in each of the 3 blocks, which resulted in 24 plots. Soil erosion was measured with sediment traps for 1 year, beginning 9 months after site preparation. Although the drum-chopped plots produced minimal erosion, the windrowed sites produced a mean of 6.8 Mg/ha. This study shows that substantial soil erosion may occur even on gentle slopes when site preparation practices such as windrowing are implemented that remove or bury the forest floor. In addition, it also demonstrates that soil erosion may be effectively controlled by forest practices that minimize areas of bare soil.

In general, mechanized harvest operations compact soils, thus increasing bulk density and decreasing both aeration porosity and saturated hydraulic conductivity (Campbell et al. 1973). Gent et al. (1984) investigated changes in soil physical properties to a depth of 0.3 m for clayey, kaolinitic, thermic, Typic Hapludult soils in the Piedmont of North Carolina in response to whole-tree harvesting (low traffic area), skidding (high traffic area), and site preparation methods that included shearing/windrowing/double disking or chopping/burning. Soils were slightly above field capacity during harvest and site preparation. Soil physical properties of skid trail plots were impacted to a greater depth (0.22 m) in comparison with whole-tree harvest plots (0.17 m). Disking restored soil physical properties to preharvest levels in the upper 0.07 to 0.12 m of soil. This study is further evidence that the greatest impacts to soils during a typical harvest operation are associated with highly trafficked, bare soil areas such as roads and skid trails. In addition, on sites with steeper slopes, decreased saturated hydraulic conductivity can increase overland flow and therefore, soil erosion potential.

Grace and Carter (2001) quantified the effect of harvesting and site preparation on sediment and runoff yield from a 20-yr-old loblolly pine plantation with sandy loam soils and slopes ranging from 3 to 15 percent in the southern Piedmont in Alabama. Following a 25-ha clearcut, site preparation treatments were: (1) shearing, ripping, bedding, and machine planting on contour; and (2) machine planting on contour. Treatments were compared with an unharvested control site. During the 20-month study period, soil erosion rates were 0.08, 0.16, and 1.02 Mg/ha for the unharvested control, Treatment 1, and Treatment 2, respectively. The more intensively site-prepared plot (Treatment 1) was characterized by greater surface cover and roughness than Treatment 2 and thus greater protection against soil loss resulting from several high-intensity rain events. This finding indicates that rainfall timing and intensity may greatly influence soil erosion rates associated with forestry practices and reflects the apparent effectiveness of BMP implementation. In addition, the results of this study emphasize the importance of forestry operations (e.g., bedding) that maintain or create adequate surface roughness to allow for infiltration and decreased velocity of surface runoff. However, more studies are needed that quantify not only erosion rates from harvest operations, but also sediment delivery to adjacent water bodies in order to evaluate and improve low-impact forestry practices. For example, Hewlett (1979) estimated that for a typical forest operational unit, 5 percent of the detached soil reaches the stream channel.

Biomass Harvesting

In response to current woody biomass demand, chipping of logging residues, such as limbs, tops, and other nonmerchantable material is being incorporated into some conventional timber harvesting operations to produce biomass fuel chips. Despite many benefits of biomass as an alternative energy source, there is some concern that the use of nonmerchantable material for energy production at the expense of erosion control may increase soil loss and stream sediment concentrations. Barrett et al. (2009) used the universal soil loss equation as modified for forests (USLE - Forest) to estimate erosion rates on a biomass harvesting case study site in the Piedmont of Virginia (Dissmeyer and Foser 1984). Estimated annual erosion rates for the biomass harvest ranged from 7.2 to 19.3 Mg/ha as compared with erosion rates of less than 2.2 to 11.2 Mg/ha for a similar conventional Piedmont harvest. Some states have already begun making additional recommendations for BMP implementation for biomass harvests. The authors concluded that more research is needed regarding the effects of biomass versus conventional harvesting on soil erosion before additional BMPs for biomass harvesting are recommended.

Roads, Skid Trails, Stream Crossings, and Streamside Management Zones

Soil erosion increases associated with forest roads and trails have been widely identified as the dominant nonpoint source of sediment pollution attributable to forest silvicultural activities (Croke and Hairsine 2006; Grace 2002, 2005; Jordan 2006). Recently, the U.S. Court of Appeals of the Ninth Circuit ruled that logging roads should be considered point sources of pollution, therefore deciding that forest roads cannot be considered exempt from National Pollutant Discharge Elimination System (NPDES) permit requirements of the Clean Water Act under the Silvicultural Rule (Boston and Thompson 2009, U.S. Court of Appeals for the Ninth Circuit 2011). The Ninth Circuit ruled that forest roads are point sources when runoff is confined and re-routed through well-defined conduits, such as ditches and culverts, which ultimately flow and transport sediment into streams and rivers. Although the ruling currently applies to roads within the jurisdiction of the Ninth Circuit in Oregon, both public and privately owned forest roads throughout the Nation may require NPDES permits. This ruling emphasizes the importance of forest roads to water quality, forest operations, and national water policy decisions.

Roads

Forest roads are an integral component of forest harvesting operations, and timber harvests are conducted on approximately 4,000 km^2 of Virginia forest every 4 to 5 years. The potential for water quality degradation due to forest roads is widely recognized (Luce 2002). The degree of water quality impacts of forest road erosion depends on the delivery ratio of soil erosion to streams. Sediment is primarily delivered to streams through surface overland flow. Hydrologic connectivity between the road and stream networks depends on factors such as gully formation (Croke and Mockler 2001, Wemple et al. 1996) and mean annual precipitation (National Research Council 2008), but is inversely proportional to water control road features, such as waterbars, turnouts, and relief culverts (National Research Council 2008). Lakel et al. (2010) and Ward and Jackson (2004) found sediment delivery ratios from forest operations (including roads) to be approximately 10 to 25 percent, but forest roads alone can have higher delivery ratios. Dymond (2010) examined the influence of forest roads on water yield and concluded that road density effectively increased watershed stream density and stream flashiness. This conclusion implies that roads disproportionately increase water yields and sediment.

In a catchment modeling study of road effects on hydrology in two heavily logged, small catchments on the western slopes of the Cascade Mountains in the Pacific Northwest, Storck et al. (1998) used the Distributed Hydrology-Soil-Vegetation Model (DHSVM) and found that forest roads increased peak flows for the largest storm events by approximately 17 percent. However, Surfleet et al. (2010) found that roughly 25 to 50 percent of DHSVM-simulated storm volumes and peak flows for road ditches were outside the uncertainty bounds of a generalized likelihood estimation procedure. This result indicates substantial variability in modeled road runoff and emphasizes the need for studies that evaluate uncertainty in both model input parameters and predictions to evaluate model performance in accurately representing field hydrologic and soil erosion processes.

Road contribution of sediment to total export at the watershed and basin scale is highly variable. Turton et al. (2009) studied sediment yield to streams for unpaved roads in Oklahoma and estimated that roads may contribute up to 35 percent of the total sediment load for a large watershed (715 km^2). However, Sheridan and Noske (2007) found that near-stream unsealed forest road surfaces contributed only 4.4 percent of the total sediment load for a 135-km^2 watershed in southeastern Australia. Gravel application to bare road surfaces substantially decreases soil erosion (Kochenderfer and Helvey 1987).

Skid Trails

Wade et al. (2012) used a randomized complete block design to evaluate several skid trail closure techniques and ground cover BMPs for their performance in bare soil stabilization and erosion control. The study location was in the Virginia Piedmont, with slopes of 10 to 15 percent and sandy clay loam, fine, kaolinitic, mesic, Typic Kanhapludults. Treatments were: (1) water bars (control); (2) water bars plus seeding; (3) water bars, seeding, and straw mulch; (4) water bars plus hardwood slash; and (5) water bars plus pine slash. Sediment was captured at the base of the plots by geotextile sediment filtration bags and weighed following rain events and at monthly intervals to obtain sediment weights.

Three soil erosion models were used to compare measured soil erosion with modeled soil erosion: USLE, the Water Erosion Prediction Project (WEPP) for forest roads, and the revised universal soil loss equation v.2 (RUSLE2). Mean annual erosion rates for the treatments were 137.7 Mg/ha for the control, 31.5 Mg/ha for the seeding treatment, 8.9 Mg/ha for the hardwood slash treatment, 5.9 Mg/ha for the pine slash treatment, and 3.0 Mg/ha for the mulching treatment. In general, USLE, WEPP, and RUSLE2 correctly predicted the order in which treatments afforded the best erosion control, which demonstrates their utility in BMP evaluation. Results indicate that for areas of high erosion potential, water bars alone may be a poor choice for water quality protection due to their lack of soil stabilization. The best choices appear to be application of logging slash (see also Sawyers et al. 2012) or mulching. Slash may be the most advantageous choice because it is readily available on harvest sites and has a slower decomposition rate than straw mulch.

Stream Crossings

Sediment delivery is of particular importance at forest road stream crossings (Lane and Sheridan 2002), which represent the most direct pathway for overland flow and sediment to stream channels. Therefore, sediment delivery ratios for forest road approaches to stream crossings should be determined in order to implement management strategies for minimizing sediment that has the highest probability of reaching the stream. The 2010 Virginia Department of Forestry (VDOF) BMP audit indicated that improper BMP implementation at stream crossings was the most important problem identified from forest operations in Virginia (Lakel, pers. comm.).

Forest road approaches to streams, as well as stream crossings, have the potential to deliver the greatest quantity of sediment to streams during forest operations (Carroll 2008, Swift 1986, Taylor et al. 1999). Installation of crossing structures requires heavy equipment trafficking over sensitive stream banks, through riparian zones, and potentially in the stream channel itself. In addition to sedimentation from equipment, sediment can run directly to streams from forest road approaches. Fords introduce sediment to streams as vehicles drive over the stream bed. Culvert installation, which involves excavation and fill work, can introduce 10 or more times the amount of sediment than a logging operation (Swift 1986, Taylor et al. 1995).

Taylor et al. (1995) make a strong case for the use of portable longitudinal glued-laminated (glulam) deck timber bridges for stream crossings on temporary low-volume roads. Advantages of portable timber bridges include their light weight and ease of fabrication, transport, installation, and removal. Because portable timber bridges are re-usable (up to 10 times or more), installation cost is comparable to that of a permanent corrugated metal culvert at $2,550 per installation (Taylor 1995). In addition, a major advantage for water quality protection is that glulam bridges may be installed and removed with skidders or hydraulic knuckleboom loaders without operating the equipment in the stream channel (Carroll 2008).

McKee et al. (2010) surveyed logging contractors from the major physiographic regions of Virginia (Mountains, Piedmont, and Coastal Plain) to better understand the most typical stream crossing types installed, the total cost associated with purchasing and installing stream crossings, and type and cost of closure BMP implementation. The authors found that more stream crossings are used for skidders than for log trucks across all physiographic regions. Bridges are most commonly used for stream crossings in the Piedmont, whereas culverts predominate in the mountains. Associated costs are highest for steel bridges, followed in descending order by costs for wooden bridges, culverts, and fords. The most commonly used stream crossing closure BMPs include a combination of waterbars, seeding, and mulch. Additional BMPs are covering roads with slash and installing water turnouts. These BMPs have been shown to be generally effective in water quality protection (Carroll 2008). The cost of BMP closure implementation ranged from $445 to $655 per crossing, with greater costs associated with BMP installation in the Mountain region.

Carroll (2008) evaluated upstream and downstream water quality, including sediment concentration, for 23 operational stream crossings in the Virginia Piedmont. Stream crossing structures included portable bridges, culverts backfilled with poles, culverts backfilled with earth, and reinforced fords. Water quality was monitored during four operational phases: preinstallation, postinstallation, during harvest, and post-road closure. Overall, this study found that portable bridges are the most effective for water quality protection, but that performance is also governed by road standards and approach characteristics. Importantly, this study found that the increased SMZ removal associated with permanent stream crossings may result in greater stream temperature increases.

Streamside Management Zones

In a watershed-scale experiment, Lakel et al. (2010) evaluated the sediment trapping efficacy of various SMZ widths under different levels of thinning following forest harvesting and site preparation in the Piedmont of Virginia. The study examined SMZ widths of 7.6 m, 15.2 m, and 30.4 m in which no thinning occurred, as well as 15.2-m, thinned SMZs. All SMZ widths performed equally well in trapping sediment, which indicates that SMZ effectiveness is controlled by factors other than width. Keys to SMZ effectiveness in trapping sediment include the presence of an intact forest floor and slope steepness, suggesting that SMZ width prescriptions should be made on a site-by-site basis. The implication is that through better understanding of the processes that control soil erosion, as well as BMP effectiveness in minimizing erosion and sediment redistribution, both water quality and site productivity objectives may be optimally achieved.

Lakel et al. (2010) also provided important data on soil erosion to sediment delivery ratios, determining that 3 to 14 percent of sediment from the harvested area reached the SMZ. This study not only examined SMZ sediment trapping effectiveness, but also quantified the amount and percentage of soil erosion and sediment delivery from harvest site preparation, roads, skid trails, decks, and firelines. As is most commonly found, highly compacted and bare soil areas such as roads, skid trails, and firelines contributed the most sediment to the SMZ. These areas of high erosion potential often represent a small percentage of the total operational area, but contribute the most sediment per unit area.

Rivenbark and Jackson (2004) examined the spatial frequency and physical characteristics of ephemeral concentrated flow paths entering SMZs for 30 clearcut and site-prepared industrial forest operational units in the Georgia Piedmont. The impetus for this study was to aid in the understanding of where and why BMPs fail to prevent sediment from being transported to stream channels. Breakthroughs were defined as surface overland flow (and sediment) pathways that invaded the SMZ and reached the stream channel. Areas of convergence (swales) and gullies accounted for about 50 percent of all breakthroughs. Concentrated runoff from roads and skid trails was identified as the cause of 25 percent of the breakthroughs. In general, large contributing areas (mean = 0.4 ha), minimal litter cover, and steep slopes characterized the locations where breakthroughs occurred. In some cases, overland flow traveled more than 30 m through SMZs before reaching the stream channel. The authors concluded that improvements to increase BMP effectiveness include maximizing ground cover, improving road runoff dispersal, increasing resistance to probable surface overland flow paths, and selectively increasing SMZ widths in problem areas.

Swift (1986) examined sediment transport distances below forest roads during and 9 months after construction in the Appalachian Mountains of western North Carolina. The objectives of this study were to evaluate the effectiveness of filter strip standards in the southern Appalachians and to test the efficacy of mulch or grass on fill slopes and of obstructions to flow within filter strips. Guidelines for filter strip widths in the eastern United States originated from the Trimble and Sartz (1957) experiment, where the slope distance of sediment transport was determined from 36 open-top culverts on partially graveled roads at the Hubbard Brook Experimental Forest in the White Mountains. Slope steepness below the road was used to make recommendations for filter strip widths to effectively trap sediment (Trimble and Sartz 1957).

Swift (1986) found that grassed fill slopes, filter strips with intact forest litter cover, and brush barriers, such as logging slash and hay bales, were most effective in reducing sediment deposit length. Importantly, this study showed that filter strip width may be reduced if the aforementioned BMPs are implemented correctly, again implying that increased filter strip width does not necessarily mean that more sediment will be trapped. Filter strip width recommendations should be made on a case-by-case basis and should take into account slope steepness, forest litter layer condition, erosion potential from human-made drainage structures (e.g., road ditches and culverts), natural areas of convergence (e.g., gullies and swales), soil erosivity, and climate. In addition, the duration of soil exposure should be as short as possible and limited to periods of minimum rainfall intensity.

Research Needs

Anderson and Lockaby (2011) identified the following four categories of research gaps related to forest operations and stream sedimentation: timber harvesting effects on water yield and water quality, temporal and spatial scale of sediment delivery, sediment and water yield from roads, and assessing the effectiveness of BMPs. Increases in stormflow volumes and peakflows following harvest operations may increase within-channel erosion, particularly in streams that are heavily impacted by legacy sediments. Legacy sediments confound evaluations of contemporary forest management practices because it is difficult to separate water quality impacts from past and present land use (Jackson et al. 2005). Incorporation of tracers (isotopic and radionuclide) to track sediment movement and statistical tools (Aikaike's Information Criterion and multivariate approaches) in current and future forestry studies could greatly improve understanding of different sediment sources (Anderson and Lockaby 2011).

We know that the majority of sediment associated with forest operations is generated from relatively small problem areas that are often non-uniformly distributed throughout the operational area. Often, these problem areas are associated with stream crossings and their associated skid trail and haul road approaches. Better quantification of soil erosion to sediment delivery ratios under various levels of BMP implementation is critical to improve the efficacy of reduced-impact forest practices. We also know that when BMPs are properly installed during forest operations, water quality generally remains unimpacted (Aust and Blinn 2004). However, more cost-benefit analyses of BMP implementation are required to achieve the major objectives of sustainable productivity and water quality protection at minimal cost.

In addition, more research is necessary to understand the impact of major rainfall events on the performance of BMPs in reducing soil erosion and sediment redistribution. Many studies are short in duration (<4 years) and may be heavily influenced by one or more major storm events. Conversely, a lack of rainfall may give undue credit to BMP effectiveness in protecting water quality. Simply put, rain events govern study findings (Anderson and Lockaby 2011). Rainfall simulation studies allow researchers to test BMP effectiveness over any desired range of rainfall conditions.

Much of the research specifically regarding forest roads and water quality in the United States has originated in the West (Anderson and Potts 1987, Litschert and MacDonald 2009, Reid and Dunne 1984). Far fewer studies investigate sediment delivery from forest roads in the East, with the exception of research at Coweeta and Fernow. Intensive forest management in the Piedmont has given rise to an extensive network of forest roads and stream crossings in this region, where sediment delivery to upland headwaters has important water quality implications for the protection of downstream water bodies (Freeman et al. 2007). It is impractical, if not impossible, to monitor stormflow and soil erosion from all road and skid trail crossings through field experimentation. Therefore, models that are readily applicable to land management programs and that accurately represent hydrologic and soil erosion processes at the catchment scale are critical to predict site- and regional-scale impacts to water quality. These hydrologic and soil erosion models may be used to assist land managers in identifying high-risk areas for erosion and implementing appropriate BMPs for water quality protection. However, models must be evaluated to determine their utility in accurately representing field hydrologic conditions and sediment delivery ratios across a broad range of conditions.

Several state and federal agencies, such as VDOF and the U.S. Department of Agriculture (USDA), Forest Service are interested in determining the applicability of the WEPP model for predicting sediment production from forest roads. The WEPP model is a physically based soil erosion and hydrologic model developed by the USDA Natural Resources Conservation Service and Forest Service that estimates soil loss and sediment yields from hillslope erosion at the small catchment scale (Flanagan and Nearing 1995). This model is capable of partitioning soil loss and sediment yields associated with roads into individual road features, such as the road surface, cutslope, fillslope, ditch, and lower hillslope (Fu et al. 2010). Previous studies have shown that WEPP is a useful tool for estimating soil erosion from surfaces with low infiltration rates, such as forest roads, where overland flow is the dominant hydrologic process (Croke and Nethery 2006, Dun et al. 2009, Elliot et al. 1999, Fu et al. 2010, Grace 2005, Laflen et al. 2004), but it has not been evaluated in the field for a wide range of forest roads and rainfall conditions.

Measurement of sediment yield and sediment delivery is highly variable, even under well-controlled field experiments. For example, Fu et al. (2010) describe variation as a result of differences in methodology. Much uncertainty exists in measured sediment yields when sediment trap data are used to estimate total sediment yields. Roadside sediment traps effectively sample coarse sediment yields but may miss the finer sediment fractions of total sediment yield. In addition, road erosion rates display a wide range of variability across different areas owing to differences in rainfall timing, frequency, and intensity, as well as topography, slope, frequency of traffic and maintenance, and surface type. For example, Brooks et al. (2006) state that because measurements of soil erosion are so highly variable, predicted erosion rates should not be assumed to be more accurate than ± 50 percent. Laflen et al. (2004) reviewed published studies related to WEPP goodness-of-fit and suggest that without calibration, WEPP performs as well as USLE - Forest. When controlled field experiments or databases of site-specific characteristics are used to parameterize the model, WEPP has the potential to be an effective tool for watershed managers.

Because WEPP mainly considers overland flow, it is currently best suited to predict runoff and soil erosion on surfaces where overland flow dominates hydrologic processes. Substantial variability exists in model predictions of runoff and sediment yield in disturbed forest settings that are dominated by subsurface flow processes (Wu et al. 2000). However, a strong case can be made that for modeling sediment yield and delivery, which are governed by overland flow, WEPP performs best where it is needed the most (i.e., forest roads and skid trails). Therefore, WEPP can be very useful for small, high-risk road segments, such as road approaches to stream crossings. However, to compare relative sediment delivery ratios between roads and other forest practices not dominated by overland flow, model performance must be improved.

Further modifications to the processes that control subsurface flow within the WEPP model are necessary to better estimate runoff and erosion at the catchment scale. In addition, subsurface flow interception by forest roads should be considered in future modifications to the model. Controlled field experiments on forest roads and other disturbed forest areas (harvested, burned, site prepared) across a broad range of landscapes are necessary to test WEPP representation of hydrologic and soil erosion processes and evaluate uncertainty in model predictions.

SUMMARY

This review concentrated on soil erosion and sediment delivery associated with reduced-impact forest operations in the Piedmont region. General results indicate that soil erosion per unit area is greatest for roads and skid trails, while comparatively less for harvested and site-prepared areas. Implementation of BMPs is most effective in water quality protection when prescriptions are made on a case-by-case basis and guided by characteristics such as percentage of bare soil, slope steepness, topographical features such as gullies and swales, and rainfall timing and magnitude. Much more is known about soil erosion rates, as opposed to sediment delivery ratios for various forest practices.

Future research should use sediment tracing methods to identify sediment source areas that are often a small percentage of total forest operations and non-uniformly distributed. Coupling of well-controlled hydrologic/soil erosion field studies and soil erosion modeling is beneficial because it provides much-needed measurements of soil erosion and sediment delivery with which to calibrate and evaluate soil erosion model performance, as well as BMP performance under changing land use scenarios.

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ASSESSMENT OF FRESHWATER WITHDRAWALS AND AVAILABILITY FOR MARCELLUS SHALE NATURAL GAS DEVELOPMENT: A CASE STUDY IN PENNSYLVANIA

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Abstract.—To evaluate surface water withdrawals used for Marcellus shale natural gas development and to assess potential impacts on water yield, a regional water balance model was developed for the Pine Creek watershed, located primarily in Lycoming County, Pennsylvania. Marcellus shale development has increased rapidly in Lycoming County since 2007. We used precipitation, potential evapotranspiration, and streamflow from a long-term U.S. Geological Survey station to estimate surface water availability and characterize seasonal changes over a 50-year period. We compared water availability and demand before Marcellus exploration to conservative projections of future water withdrawals for Lycoming County. Results show an increase in total surface water withdrawals related to mining use in Lycoming County. We thus were able to estimate current surface water reserves in the area.

INTRODUCTION

With the development of new horizontal drilling technologies and the ever-increasing demand for energy, the economic feasibility of unconventional natural gas development in the Marcellus shale regions of New York, Pennsylvania, Ohio, and West Virginia is greater than ever before. The U.S. Department of Energy's National Energy Technology Laboratory estimates recoverable natural gas reserves to be as high as 489 trillion cubic feet although these numbers are revised frequently (Arthur et al. 2010).

Several factors have contributed to interest in unconventional natural gas reservoirs such as those present in the Marcellus shale formation. These factors include advancements in horizontal drilling technology and hydraulic fracturing, along with the increase in natural gas prices (Ground Water Protection Council and ALL Consulting 2009). Natural gas is gaining momentum in the United States' energy portfolio and accounted for 25 percent of all energy consumption by fuel type in 2009 (U.S. Energy Information Administration 2010). Much of the increased production of natural gas is due to new techniques in capturing natural gas from unconventional sources (U.S. Energy Information Administration 2010). Unconventional reserves are located in tight, low-porosity formations and differ from conventional reservoirs, which have greater porosity and allow the oil or gas to move within the pore space more naturally.

Marcellus shale exhibits these "tight" formation features, which often consist of sandstone but also take the form of organic rich material, as with coalbed methane and shale gas. The Marcellus formation lies between 4,000 and 8,000 feet below ground level, which are typical drilling depths in Pennsylvania (Blauvelt 2010). Due to the nature of Marcellus shale, hydraulic fracturing techniques

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are used to increase porosity and to facilitate movement of the trapped gas. In this process large volumes of water are mixed with sand and chemicals that are pumped under high pressure down the well column. This pressure creates fissures in the shale which are held open by the sand particles. Gas is then able to flow from the formation up the well. Horizontal drilling also plays an integral role in the process. By allowing for increased exposure to the shale, horizontal drilling has greatly reduced the number of well pads needed for development and has vastly increased the production of wells (Blauvelt 2010).

The process of hydraulic fracturing typically uses between 3 and 5 million gallons (Mgal) of water per well per year, but usage can vary significantly (Abdalla and Drohan 2010). Although much of this water is lost to the Marcellus formation, recovered water known as produced water, is treated as a waste product and is reused many times. To put these numbers in perspective, these volumes are significantly less than consumption for other energy sources and for public use. However, water usage for Marcellus shale hydraulic fracturing operations is consumptive, meaning that water sources removed from the ground or surface water are not directly returned to the same basin for future use. Volumes of water are withdrawn in a short amount of time, which could pose problems for smaller watersheds during droughts. The focus of our study was the Pine Creek watershed in north-central Pennsylvania. This watershed is primarily located in Lycoming County, where surface water withdrawals have recently increased.

Pine Creek watershed is located in one of the six primary sub-basins of the Susquehanna River Basin (SRB), which lies in sections of New York, Pennsylvania, and Maryland. The SRB encompasses more than 27,500 mi^2 and makes up 43 percent of the Chesapeake Bay watershed. The four sub-basins located in Pennsylvania are the Middle Susquehanna, West Branch, Juniata, and Lower Susquehanna. Pine Creek is located in the West Branch of the Susquehanna sub-basin, which covers 6,992 mi^2 of central Pennsylvania and is the largest sub-basin in the SRB. Approximately 72 percent of this area is underlain with Marcellus shale (Susquehanna River Basin Commission 2010).

A multi-state jurisdictional commission called the Susquehanna River Basin Commission (SRBC) has established 12 priority watersheds, of which 5 priority watersheds are located in the West Branch of the Susquehanna. The SRBC has the authority to create and enforce regulations within the SRB (Arthur et al. 2010). All activities pertaining to surface or groundwater withdrawals in the SRB must be approved by the SRBC. A new SRBC ruling went into effect on January 15, 2009, which allowed for increased efficiency in the regulatory permitting process and aided in stream protection through monitoring, reporting, and mitigation (SRBC 2009). In assessing the withdrawals in rivers and streams, the SRBC uses passby flow, which it defines as "a prescribed quantity of flow that must be allowed to pass a prescribed point downstream from a water supply intake at any time during which a withdrawal is occurring." This passby flow requirement is based on estimates of 7Q-10, defined as follows: "the lowest average, consecutive 7-day flow that would occur with a frequency or recurrence interval of one in ten years. A 10-year low flow event has a 10 percent chance of occurring in any one year. Accepted hydrologic practices must be used to determine the 7Q-10 flow" (SRBC 2009). The 7Q-10 requirements must be included in the water management plan that is completed by each company in the permitting process. Also included in the low-flow analysis is the average daily flow at the point of withdrawal, along with the drainage area.

The sustainability of water withdrawals at the county level across the United States was evaluated by Roy et al. (2005). This study provided a summary of the nation's large-scale use of freshwater and included projected findings to the year 2025. The report outlined three key areas that required further investigation. These key areas were in-stream use requirements to maintain optimal habitat and beneficial uses, water storage and withdrawal capacity available, and more temporally detailed patterns of water use (Roy et al. 2005). Applying methods outlined in this report to address withdrawals at a more localized level would help to identify issues relevant to the Pine Creek Valley. This approach will allow use of local water consumption data as opposed to national estimates provided in the report by Roy et al. (2005). These data should allow for a more accurate analysis of water use and subsequent availability in Lycoming County. The objectives of our research are to evaluate surface water withdrawals in Lycoming County used for Marcellus shale natural gas development and to assess potential impacts on water yield. This research will estimate conservatively future water withdrawals and compare demand and availability pre- and post-Marcellus exploration.

METHODS

A regional water balance model was developed for the Pine Creek watershed. The drainage area of the Pine Creek watershed at the U.S. Geological Survey (USGS) station in Waterville, PA is approximately 950 mi^2. To characterize seasonal changes in discharge of the Pine Creek watershed, 50 years worth of streamflow data, collected by USGS stream gauges near Waterville, Pennsylvania, were evaluated (USGS 2011). Precipitation was collected from several stations in the watershed and combined to approximate average annual and monthly precipitation (National Climatic Data Center 2011).

By using the long-term annual water budget analysis produced from Roy et al. (2005), estimates of surface water availability were evaluated for Lycoming County. County-level water use estimates from USGS were updated to account for the recent increase in Marcellus shale exploration. Current estimates of Marcellus shale drilling activity were obtained from the Pennsylvania Department of Environmental Protection (DEP), which reported the drilling of 106 horizontal Marcellus wells in Lycoming County in 2010. Under the assumption that water withdrawals for Marcellus shale development occur in the same county where the drilling occurred, a conservative estimate of average water consumption per well (2.8 Mgal yr^{-1}) was added to water use in the mining category for 2010. We assumed that water use remained constant in all categories with the exception of mining. Total surface water withdrawals were then compared to all withdrawals for mining use, including shale gas production. The amount of renewable water for the region, determined by subtracting potential evapotranspiration from precipitation summed for all months in which precipitation exceeds evapotranspiration, as outlined by Roy et al. (2005), was then compared to the updated USGS data.

RESULTS AND DISCUSSION

Average annual monthly discharge, expressed as a depth measurement, is approximately 42 mm. Showing seasonal variability, monthly discharge in June through November is below this average; the average August level is approximately 13.5 mm. These individual monthly low flows relative to the average most likely reflect the annual cove hardwood growing season and the corresponding water uptake. Between December and the middle of May, a surplus of water, relative to the average, is observed, peaking in April with approximately 93 mm of discharge. During this time, frozen or saturated soils facilitate runoff of precipitation. Runoff and lack of interception of precipitation by deciduous trees translate into increased water levels. Figure 1 shows monthly discharge and precipitation averages from 1958 through 2010. By outlining the seasonal variability of the Pine Creek watershed, it can easily be determined which months are most susceptible to potential biological, recreational, and other impacts from surface water withdrawals. In 2010, drilling activity occurred more frequently in these months (June through September), as summarized in Table 1.

Average annual discharge and precipitation were evaluated for the Pine Creek watershed from 1958 through 2008 (Fig. 2) to distinguish between high-flow and low-flow years. Although no trends can be determined based on this snapshot in time, we can see that average annual discharge is

Table 1.—Marcellus wells completed in Lycoming County, Pennsylvania, in 2010

Number of wells drilled by month in 2010											
Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
5	12	1	5	9	17	13	7	13	4	14	7

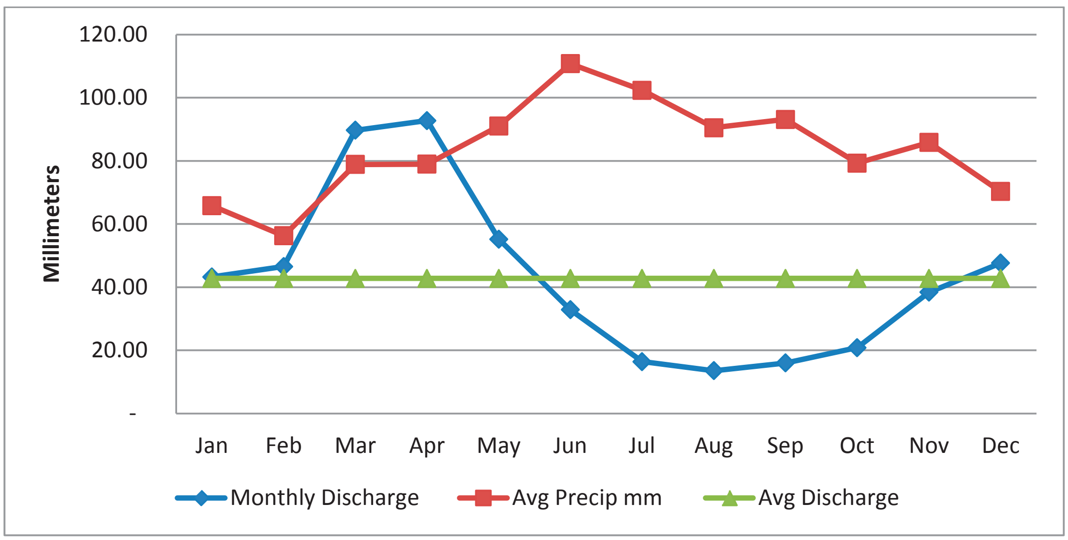

Figure 1.—Average monthly discharge and precipitation in the Pine Creek watershed, 1958 through 2010.

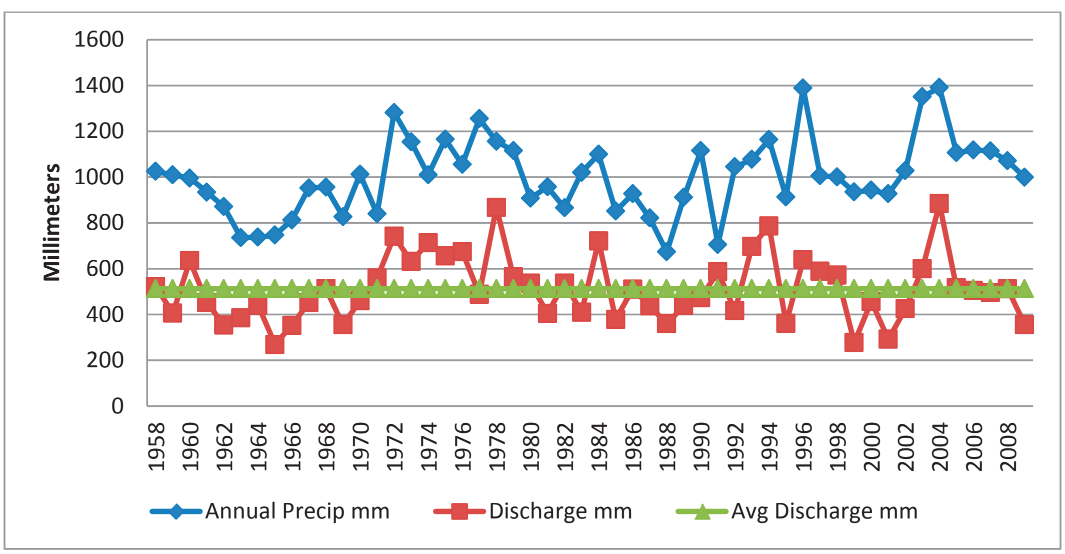

Figure 2.—Average annual discharge and precipitation in the Pine Creek watershed, 1958 through 2008.

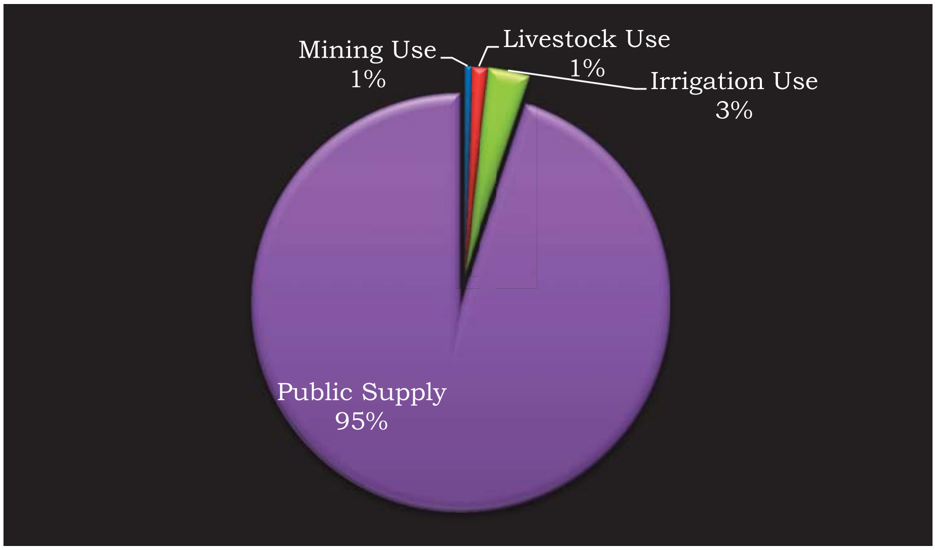

Figure 3.—Surface water withdrawals by category, Lycoming County, Pennsylvania, 2005.

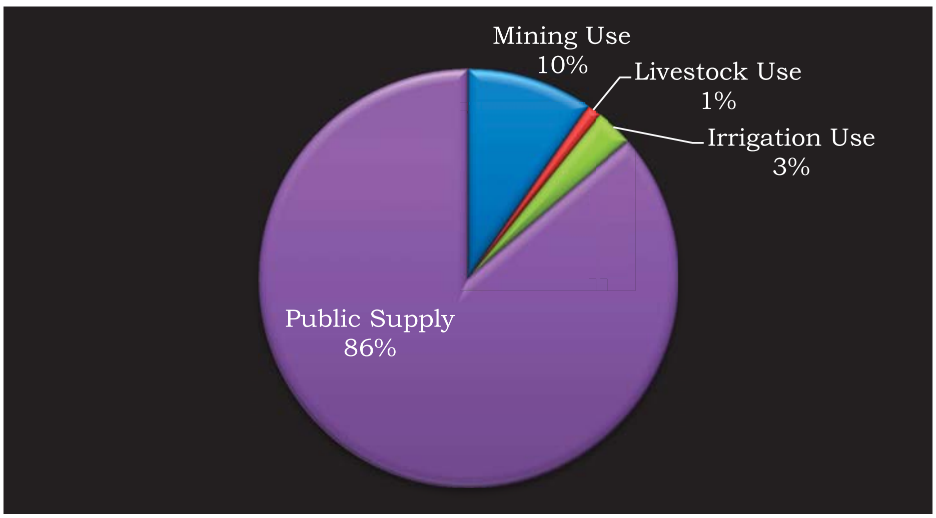

Figure 4.—Surface water withdrawals by category, Lycoming County, Pennsylvania, 2010.

approximately 512 mm, expressed as a depth measurement. Approximately 30 years of data recorded since 1958 have shown below-average flows; the lowest years on record were 1965 and 2001. The highest discharge years were 1978 and 2004, averaging almost 900 mm. In general, high and low precipitation years correspond to high and low average discharge (Fig. 2) although high or low discharges do not necessarily result in flooding or drought events. For example, one of the worst flooding events of this period occurred in 1972, which is not shown as the highest discharge year. Flooding is a response to several factors and usually is caused by the rate at which precipitation or other inputs occur.

In 2005, Lycoming County had four primary categories of surface water consumption: irrigation, livestock, mining, and public supply (Fig. 3). Approximately 95 percent of all surface water withdrawals in the county were used for the public water supply, and less than 1 percent was consumed by mining operations. We estimated use rates for the mining category under the conservative assumption of 0.0077 Mgal day^{-1} per well. Under this assumption, freshwater withdrawals used for mining purposes increased twentyfold between 2005 and 2010, from 0.04 Mgal day^{-1} in 2005 to 0.86 Mgal day^{-1}. Figure 4 shows the updated proportions of surface water withdrawals by category for 2010.

CONCLUSIONS

Natural gas extraction will undoubtedly have an enormous economic impact by creating jobs and increasing state revenue while boosting local economies. With this opportunity comes increased concern from local residents and environmental organizations over potential adverse impacts. Assessments of water withdrawals used for developing the Marcellus shale are necessary to properly evaluate potential effects on forested watersheds. Research on water availability in these catchments and cumulative effects of natural gas extraction on discharge could provide insight into the broader impacts of regional gas development on future water withdrawals.

Assuming development of the Marcellus shale formation continues in Pennsylvania and water withdrawals in the West Branch of the Susquehanna sub-basin remain necessary for this development, an increased value will be placed on water resources in Lycoming County and the Pine Creek watershed. Cumulative effects on discharge will become increasingly important knowledge to protect the ecological integrity of the area.

With freshwater vital to this exploration, increased importance should be placed on analyzing and characterizing the sourcing areas such as the Pine Creek watershed. Although water volumes consumed are not large relative to other uses, the rate at which water is needed and withdrawn could potentially affect watersheds. Smaller watersheds are most susceptible to these impacts, especially in summer low-flow conditions. As Marcellus shale gas production increases, so will mining operations' proportion of surface water withdrawals in the area. Currently water management plans, required by the Pennsylvania DEP, require gas well operators to compare their own surface water withdrawals to the 7Q-10. This impact study also requires operators to outline stream uses and conduct a natural diversity inventory.

Although Pennsylvania has relatively abundant water resources, which are much greater than in other shale natural gas extraction areas, Marcellus shale development potentially still could negatively affect water availability. One option to reduce the potential impact of surface water withdrawals is to store water in months with above-average discharge. This action would reduce the impact of large withdrawals over a short period of time and take water when a relative excess is available. A deeper understanding of surface water availability at the county level would help resource managers to reduce the impact of Marcellus exploration on watersheds.

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A WEST VIRGINIA CASE STUDY: DOES EROSION DIFFER BETWEEN STREAMBANKS CLUSTERED BY THE BANK ASSESSMENT OF NONPOINT SOURCE CONSEQUENCES OF SEDIMENT (BANCS) MODEL PARAMETERS?

Abby L. McQueen, Nicolas P. Zégre, and Danny L. Welsch[1]

Abstract.—The integration of factors and processes responsible for streambank erosion is complex. To explore the influence of physical variables on streambank erosion, parameters for the bank assessment of nonpoint source consequences of sediment (BANCS) model were collected on a 1-km reach of Horseshoe Run in Tucker County, West Virginia. Cluster analysis was used to establish groups of streambanks, and observed erosion between the groups was compared. The cluster analysis revealed that groups of streambanks with uniform bank composition, high surface protection, low bank angles, and intermediate rooting depth and rooting density values tended to have less erosion. Our results suggest that the BANCS model input parameters may provide valuable insight into the susceptibility of a streambank to erosion.

INTRODUCTION

Streambank Erosion

Erosion and deposition are natural weathering processes that have been shaping the environment for millennia. Historically, sediment was thought to originate largely from surface runoff. Over the past several decades, sediment originating from streambanks has been thought to be a potentially greater source of sediment. Streambank erosion has been found to account for the majority of sediment input to streams in California (Trimble 1997), Montana (Rosgen 1973, 1976), Minnesota (Sekely et al. 2002), across the Southeast (Simon and Rinaldi 2006), and in Australia (Prosser et al. 2000), England (Lawler et al. 1999), and Ireland (Evans et al. 2006).

Streambanks erode through a combination of streambank weakening, failure of bank materials due to gravity, and detachment of bank materials due to flow (Lawler et al. 1999). The influence of each mechanism on total streambank erosion differs by stream and may vary both spatially and temporally within a single reach. Common variables that have been used to successfully predict erosion include freeze thaw cycling, soil bulk density, near bank velocities, cross-sectional dimensions, flow conditions (e.g., duration, peak), silt-clay content, and various vegetation indices (Chen et al. 2005, Julian and Torres 2006, Magner and Brooks 2008, Pizzuto 2009). Prediction models incorporating various combinations of these variables have been successfully tested at individual sites; however, there is a need to generate a model with an established set of variables that can be transferred across sites.

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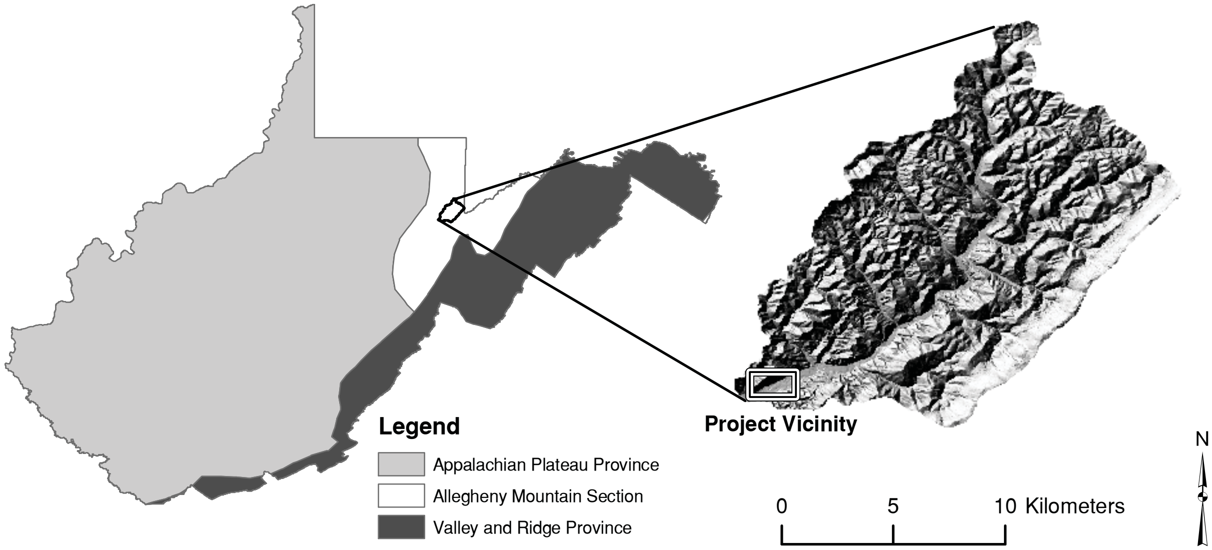

Figure 1.—The study area near the outlet of the Horsehoe Run watershed, which lies within the Allegheny Mountain Section of the Appalachian Plateau physiographic province, Tucker County, West Virginia.

Model Description

The bank assessment of nonpoint source consequences of sediment (BANCS) model was developed based on the need of practitioners and watershed managers to have a comparable, transferable streambank erosion prediction model that could be easily and rapidly applied at the watershed scale (Rosgen 2006). This model relies on observations and statistical relationships to predict bank failure and erosion. Combining two submodels, the bank erosion hazard index (BEHI) and near bank stress (NBS), with a set of regional erosion curves, the model incorporates the susceptibility of a bank to mass or gravitational failure, fluvial entrainment, and surface erosion. The BANCS model groups streambanks into 36 categories based on the BEHI and NBS parameter scores. We did not have an adequate number of streambanks in unique categories to determine if erosion differed between these categories. In lieu of this comparison, we used cluster analysis to establish groups of streambanks based on the BANCS parameters and then compared the observed erosion between these groups.

STUDY AREA

Watershed

The Horseshoe Run watershed is located in the Allegheny Mountain Section of the Appalachian Plateau physiographic province in Tucker County, West Virginia, and is approximately 137 km^2 in size at the project site (Fig. 1). The project site is 300 m upstream of the Horseshoe Run confluence with the Cheat River, which drains into the Monongahela River and then the Ohio River. The Allegheny Mountain section of the province is highly dissected with steep, high-energy streams flowing into narrow and more moderate floodplains. Watershed elevations range from 1,115 m along Backbone Mountain, the eastern ridge of the watershed, to 473 m near the outlet with an average slope of 46°. The region is characterized by a humid continental climate with average annual rainfall of 1,318 mm and an average annual temperature of 9.7 °C.

The hillslopes and upper portions of the watershed are in various stages of forest stand development due to the historic and current logging in the watershed (Fansler 1962). Land uses in the narrow floodplain range from intensively grazed to rural residential to forested. Due to the steepness of the hillslopes and the narrowness of the valley, most anthropogenic impacts span the floodplain and in some cases border or intersect the stream (Homer et al. 2007).

A series of aerial photographs revealed that Horseshoe Run has been actively migrating and eroding at significant rates over the past several decades (Canaan Valley Institute 2006 [CVI], U.S. Geological Survey 1997, West Virginia Statewide Addressing and Mapping Board 2003). This migration can be attributed to a combination of natural and anthropogenic disturbances. An inherently high bedload and a history of large flooding events combined with the periodic clearing of large swaths of the hillslope and riparian zone for logging, agriculture, and rural development contribute to the erosive nature of the stream.

Reach Characterization

Streambanks through the reach are characterized by a thin layer of cohesive silt loam in the upper bank overlaying layers of soil mixed with gravel and cobble. Floodplain soils through the reach are classified as Gilpin channery silt loams, Philo silt loams, or a mixture of alluvial material of the Fluvaquents-Udifluvents complex (Losche and Beverage 1967). Stream cross-sectional area averaged 85 m^2 with an average width of 83 m and depth of 1 m. The average bed slope was 0.0059 m/m and the substrate ranges from fine gravel to large cobble with a D50 (defined as the grain diameter at which 50 percent of the sediment sample is finer than that size) of very coarse gravel measuring 52 mm. Vegetation ranges from dense stands of American sycamore (*Platanus occidentalis* L.) to mowed grasses. River birch (*Betula nigra* L.), yellow buckeye (*Aesculus flava* Aiton), multiflora rose (*Rosa multiflora* Thunb.), autumn olive (*Elaeagnus umbellate* Thunb.), and wingstem (*Verbesina alterniflora* [L.] Britton ex Kearney) were other common species found growing adjacent to the stream.

METHODS

Data Collection

Fifteen streambank sites were selected along Horseshoe Run to represent a range of streambank conditions. Two permanent benchmarks, 45-cm lengths of 1.3-cm-diameter reinforcing bar, were pounded vertically into the ground along a transect perpendicular to the stream at each site beyond the top of the bank, from which bank profiles were aligned and measured. One horizontal benchmark, or bank pin, was installed in each bank profile where cohesive soils were present (Coffman 2009, Thorne 1981, U.S. Environmental Protection Agency 1999). Bank profiles were measured by using a laser distance finder. The laser distance finder was mounted to a stadia rod which was leveled and secured with a tripod to collect bank data.

Baseline bank profiles were measured in November 2009. The bank profiles were remeasured in October 2010 to generate annual erosion amounts for each streambank site (Henderson 2006, Pollen-Bankhead and Simon 2008, Prosser et al. 2000). The x and y bank profile coordinates were imported into ArcMap (ESRI, Redlands, CA), a polygon outlining the eroded area was created, and the area of the polygon was calculated. Cross-section data were collected at each site, from which mean and near bank maximum depths were derived (Harrelson et al. 1994).

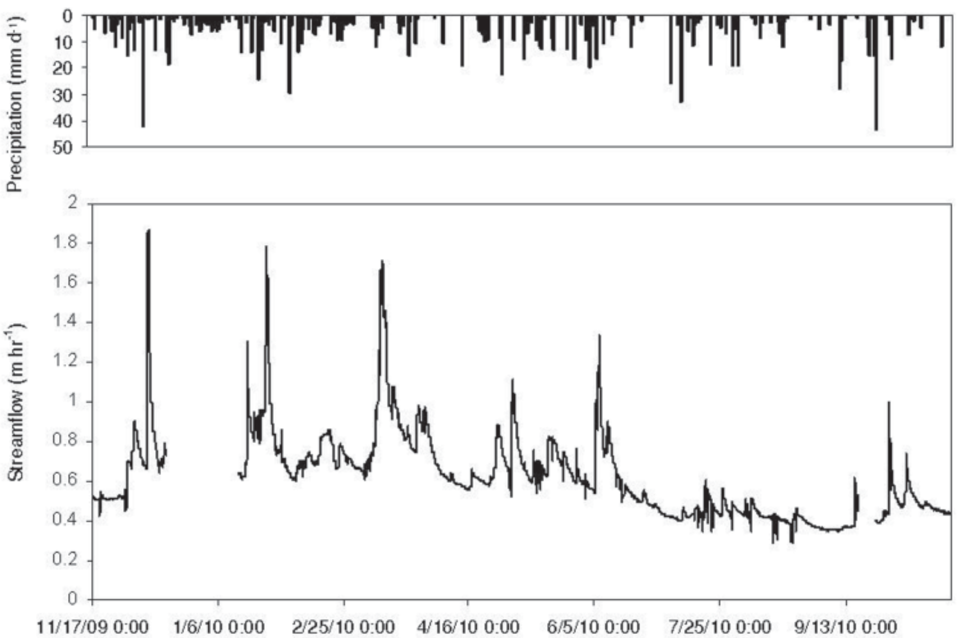

Figure 2.—Average precipitation from the Davis 3SE and Parsons 1NE National Climatic Data Center weather stations and streamflow stage from the Canaan Valley Institute stream gauge. Gaps in streamflow represent missing data.

A stream gauge installed by CVI approximately 5 km upstream of the project site on Horseshoe Run collected stage height in 15-minute intervals from November 2009 through October 2010. Lacking a weather station in the watershed, we used precipitation data from two National Climatic Data Center [NCDC] weather stations: Davis 3SE (Coop_ID 462211), located approximately 10 km east of the watershed at an elevation of 1,162 m, and Parsons 1NE (NCDC Coop_ID 466867), located approximately 6.5 km south of the watershed at an elevation of 557 m. Averaging values from the upper portion of the watershed represented by the Davis station and the mouth of the watershed represented by the Parsons station provided approximate values for the study reach (Fig. 2). Total precipitation averaged between the two stations was 1,240 mm for the study period with greater than 5 m of total snowfall.

The highest streamflow events occurred in the winter months between December and April from a combination of rainfall, snowmelt, and rain-on-snow events. Long-term data were unavailable for the CVI gauge; however, the nearby USGS Cheat River gauging station near Parsons, West Virginia (03069500) had a historic record and indicated that the January high-flow event had a recurrence interval of approximately 1.7 years, and the March flow event had a recurrence interval of approximately 1.5 years. The December high flow on Horseshoe Run was a localized event and did not have corresponding elevated discharge on the Cheat River (Fig. 2).

Model Parameters

Bank height was calculated by measuring the vertical distance from the bank toe to the top of the bank. Bankfull height was derived by fitting a trend line to the top of bank points along the longitudinal profile and calculating a height from the fitted data. Root depth was measured from the top of the bank to the terminus of the majority of roots. Root density was visually estimated from that portion of the bank considered in the root depth measurement. When bare roots were exposed in three dimensions, the percentage of volume occupied by the roots in three dimensions was estimated. When roots were exposed only on the bank face, the percentage of area occupied by the roots in two dimensions was estimated. When roots were not exposed, percentages were estimated based on the aboveground density of vegetation present.

Bank angle was measured in ArcMap by using the measure angle tool. The angle most likely influencing the gravitational failure of the bank was measured. Surface protection represents the proportion of the bank face that is protected by vegetation, large rocks, or other materials that resist hydraulic erosion. We calculated a percentage of surface protection by measuring the height or length of the bank face that was protected, typically by vegetation, and dividing this value by the total height or length of the bank. A bank material adjustment factor was determined by adding 5 to 10 points to those sites where gravel or a gravel and sand composite matrix was present. Factors were determined by the percentage of sand and gravel in the banks by using the following classification, where the rating is followed by the percentage of sand and gravel in parentheses: 5 (0-30), 6 (30-45), 7 (45-55), 8 (55-70), 9 (70-85), and 10 (85-100). Percentages were determined based on a textural classification of soils in the laboratory (American Society for Testing and Materials 1988). A stratification adjustment factor was assigned for those banks in the upper reach that were stratified. Adjustment ratings were assigned as follows: 5 for banks with stratification but without preferential erosion; 8 for banks exhibiting any stratified preferential erosion; and 10 for banks with preferential erosion in the lower stratified layers, preferential erosion below the root zone, or both. The minimum, mean, and maximum values for the collected model parameters are listed in Table 1.

Table 1.—BANCS model input parameters with associated measurement units

Parameter	Unit	Measured	Estimated/ derived	Summary data Min	Mn	Max
Bank erosion hazard index (BEHI)						
†Study bank height ratio				0.52	1.11	1.75
Bankfull height	m		X	0.83	1.48	2.03
Bank height	m	X		1.03	1.38	1.60
†Root depth ratio				0.02	0.27	0.72
Root depth	m	X		0.03	0.39	1.22
Bank height	m	X		0.83	1.48	2.03
†Weighted root density				0.17	4.95	14.44
Root density	%		X	5.00	15.20	30 .00
Root depth ratio		X		0.02	0.27	0.72
†Bank angle	degrees	X		30.00	66.43	136.00
†Surface protection	%	X		0.00	19.20	72 .00
†Bank material adjustment			X	5.00	7.60	9.00
†Stratification adjustment			X	0.00	6.00	10.00
Near bank stress index (NBS)						
†Depth ratio				0.98	1.47	2.08
Near bank max depth	m	X		0.98	1.76	2.42
Mean depth	m	X		0.77	1.24	1.88

† indicates parameters used in the cluster analysis.

x's indicate whether the parameter was measured based on data collected in the field or estimated/derived by using best professional judgment. Minimum, mean, and maximum values for each parameter are included.

Cluster Analysis

Cluster analysis using the Ward agglomeration method was run on all of the sites with the following parameters: study bank height ratio, root depth ratio, weighted root density, bank angle, surface protection, bank material adjustment, stratification adjustment, and near bank maximum depth ratio. The BEHI and NBS data were log transformed to meet normality assumptions where appropriate, scaled, and centered. Then a Euclidean distance matrix was generated from these data to be used as input to the cluster analysis. Analysis of variance was used to determine if erosion differed between the cluster groups. All statistical analyses were performed in the R language and environment, version 2.12.1 (R Development Core Team 2010).

RESULTS

The erosion at all the streambank sites ranged from 0.09 m^2 to 5.33 m^2 (mean 1.05 m^2 and median 0.41 m^2) (Fig. 3). Because data were collected along a cross-sectional transect, only two-dimensional erosion data were calculated. A third dimension measured along the length of the bank would have been required to generate the volume of erosion.

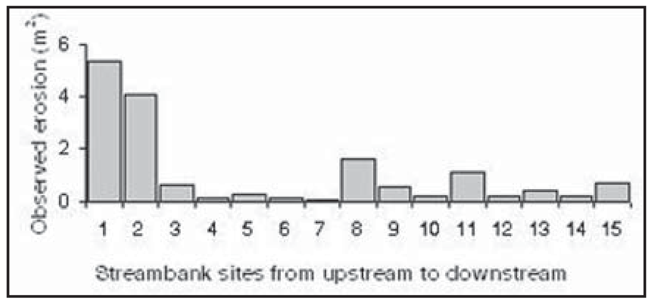

Figure 3.—Barplot of observed erosion (m^2) at the streambank sites in order from upstream to downstream.

The cluster analysis divided the streambanks into three groups: a highly stratified, densely vegetated group (Group 1), a sparsely vegetated group (Group 2), and a group with intermediate vegetation values and low bank angles (Group 3). Analysis of variance revealed that erosion differed between the cluster groups at the 0.1 significance level (p = 0.08). Boxplots of transformed erosion by cluster groups indicated that Group 3 had lower erosion amounts than the remaining sites (Fig. 4). This group of streambanks had uniform bank composition, high surface protection, low bank angles, and intermediate rooting depth and rooting density values compared to the other groups.

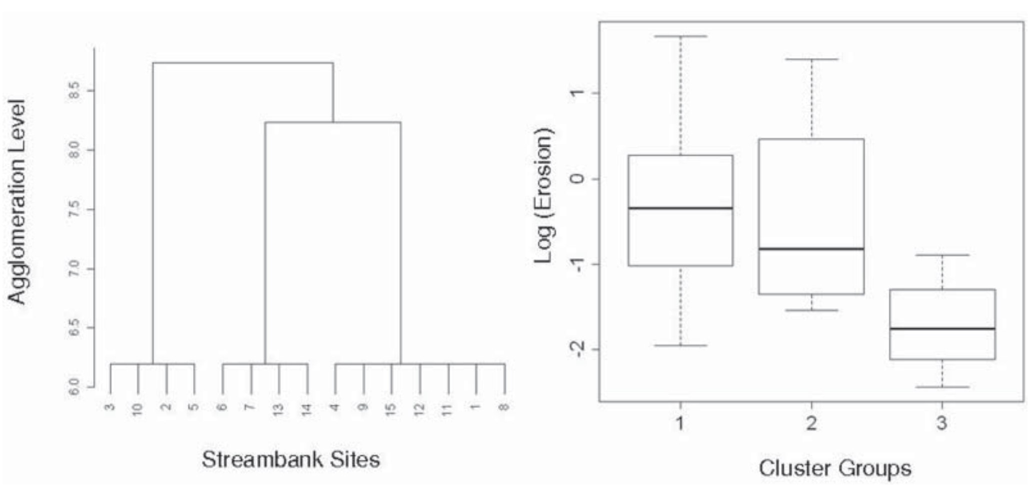

Figure 4.—Cluster analysis using the Ward agglomeration method and boxplots of log(erosion) values by cluster group.

DISCUSSION

Banks with uniform composition, high surface protection, and low bank angles were typically believed to have a lower susceptibility to erosion; however, the banks with intermediate vegetation coverage behaved in a surprising way. Vegetation has been shown to have both positive and negative influences on bank stability (Simon and Collison 2002, Wallick et al. 2006); a negative influence was evident at one site in the project reach. The site with the highest erosion (5.33 m^2) had a large tree about 1 m beyond the top of the bank. Erosion caused the bank to retreat to the tree and removed the entire root network and underlying streambank when it failed. A streambank without any vegetation may be equally vulnerable because there is no protection from surface erosion and no added cohesion from roots (Abernathy and Rutherford 1998, Wynn and Mostaghimi 2006). Studies have found that a mix of vegetation with varying sizes of root classes or grass and shrub species with high densities but low surcharge may provide the best protection, and the intermediate classes of vegetation identified in this study may support these findings (Simon and Collison 2002, Wynn and Mostaghimi 2006).

CONCLUSIONS

We used cluster analysis to establish groups of streambanks and then compared the observed erosion between these groups. When the streambank parameters were used to group sites independently of erosion, a group of streambanks with moderate rooting depths and densities and low bank angles emerged. This group had the least erosion. A variety of vegetation types with a wide distribution of root sizes and depths may provide more stability than larger vegetation with deeper, denser root networks. This relationship might be particularly true for incised streams with high hydraulic erosion at the bank toe, where the surcharge of large trees may outweigh the stabilizing effects of vegetation.

ACKNOWLEDGMENTS

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EVALUATING RELATIONSHIPS BETWEEN NATURAL RESOURCE MANAGEMENT, LAND USE CHANGES, AND FLOODING IN THE APPALACHIAN REGION

Nicolas P. Zégre and Samuel J. Lamont[1]

Abstract.—The Appalachian Region has a long history of natural resource management and recurrent history of frequent and large-scale floods. Land use activities such as urbanization, mining, forest harvesting, and agriculture can have a noticeable effect on the volume, magnitude, timing, and frequency of floods. Determining the effects of land use on flooding is difficult for many reasons, and there are no exact methods of identifying the impacts of land use on flood generation across larger scales. To ascertain the potential effects of land use changes on flooding in this region, a flood production metric was developed by using retrospective analysis between the proportions of land use and flood count data for 420 counties in 13 states. Generalized linear models were used to identify landscape and climate attributes that explain the largest variations in flood data during 2000, 2001, and 2002. Results show that forests, agriculture, riparian forest, impervious surfaces, precipitation, topographic slope, and surface coal production explain variations in floods in this region. Future changes in land use have the potential to increase or decrease flooding and should be considered in natural resource management with respect to the mosaic of land uses in the Appalachian Region.

INTRODUCTION

The ability of a watershed to mitigate or control runoff is primarily influenced by local climate, geology, and topography, as well as the nature and extent of land use conditions. Watersheds with large proportions of land use in agriculture, forest harvesting, surface mining, and urbanization are more likely to produce runoff compared to watersheds that are predominantly forested and to some extent covered with wetlands. Numerous studies have shown the importance of forested headwater catchments as they provide many valuable ecosystem services, including flood mitigation, that link the streams to the people living in these areas (Meyer and Wallace 2001). Land use activities such as urbanization (Gremillion et al. 2000), mining (Bonta 2000, Messinger 2003), forest harvesting (Zégre et al. 2010), and agriculture (Dye and Croke 2003) can have a noticeable effect on the volume, magnitude, timing, and frequency of floods.

In contrast, intact forests and wetlands mitigate storm runoff by returning water to the atmosphere through plant transpiration and interception or by temporarily storing runoff that is released over time. Additionally, runoff is a function of slope (the steeper the slope, the less the storage), latitude (regional climate), and watershed size. Land use activities that alter or remove vegetation have the potential of increasing stormflow volume by reducing the overall amount of water lost to the atmosphere through forest canopy interception and evapotranspiration, thereby increasing the volume of water delivered to a stream (Bosch and Hewlett 1982). Activities that reduce infiltration capacity of soils, such as roads, heavy grazing, surface mining, and heavy machinery, can increase

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surface runoff by translating a larger proportion of precipitation to runoff rather than being stored in soil. Roads and drainage infrastructure increase the connectivity of a watershed to the stream, resulting in reduced travel times of water and increased peakflow at the watershed outlet. Land use activities can also increase erosion and sedimentation, modifying channel geometry and thereby reducing storage capacity of the stream channel.

Determining the effects of land use on flooding is nevertheless challenging because floods along streams and rivers represent the accumulated runoff from many watersheds with heterogeneous landscape characteristics and a vast array of process interactions that are difficult to measure. In addition, flood-producing precipitation is spatially and temporally heterogeneous, unevenly distributing rainfall across the landscape. As such, there are no exact methods of identifying the impact of land use changes on flood generation across large scales.

In this study we use ordinary least squares regression, land use data, and flood count data to evaluate the integrated effects of land use changes, natural resource management, urbanization, and precipitation to explain variations in floods for counties located in the Appalachian Region.

METHODS

Study Area and Extent

The Appalachian Region (AR) consists of approximately 205,000 square miles, covering 420 counties in 13 states (Fig. 1). It extends more than 1,000 miles, from southwestern New York to northeastern Mississippi, and is home to 24.8 million people. The AR has a long history of natural resource extraction, including coal, timber, and natural gas. Though much of the region is mainly forest, large-scale changes attributed to mining and forest harvesting are the predominant driver of changes in land use and land cover in the region (Townsend et al. 2009).

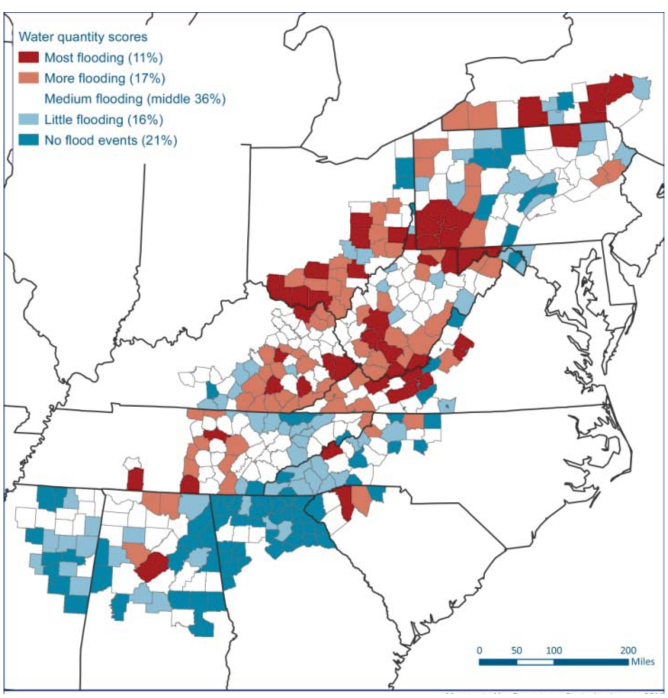

Figure 1.—Flood count data by county for the Appalachian Region. Flood count data are normalized by the number of floods per county area and are presented on a relative scale.

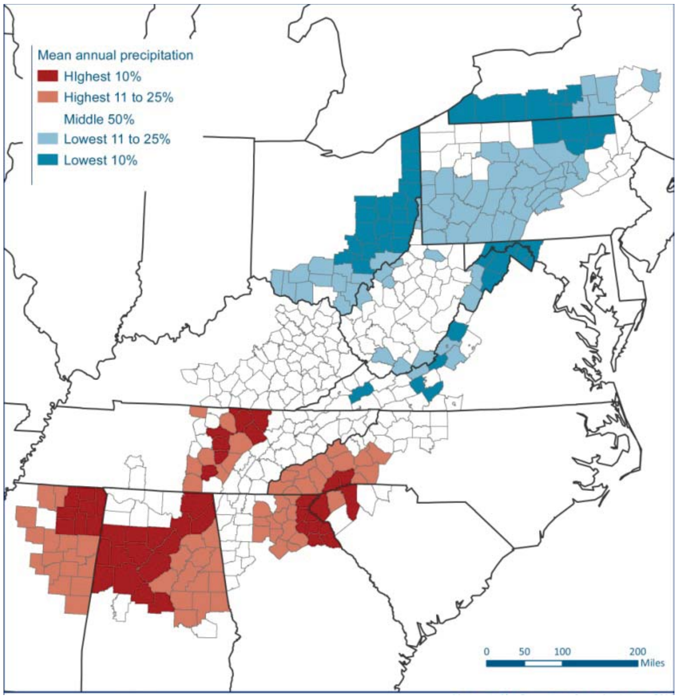

Figure 2.—Mean annual precipitation (MAP) by county for the Appalachian Region. Data are normalized by the depth of annual precipitation per county area and are presented on a relative scale.

Data and Analyses

To ascertain the potential effects of land use on flooding in AR counties, a model was developed by using retrospective analysis between the proportions of a county under given land use, climate, and flood count data. Land use for the 420 counties was derived from the 2001 national land cover dataset (NLCD). Specifically we are interested in landscape attributes that potentially mitigate or exacerbate flooding. As such, the 2001 NLCD was queried for the proportion of county under forest, agriculture, riparian forest, wetlands, and impervious surface (including roads, houses, and buildings); average topographic slope; and coal production per square mile, calculated as tons of surface-mined coal between 1983 and 2009 divided by county area.

Mean annual precipitation (MAP) from the National Oceanographic and Atmospheric Administration's National Climatic Data Center (NCDC) was included to account for regional differences in climate, namely precipitation and air temperature. When the spatial distribution of county-level MAP was mapped, a clear regional pattern emerged (Fig. 2); therefore, MAP was classified as three regions: region 1 – lower MAP range (New York, Pennsylvania, Ohio, Maryland, and Virginia), region 2 – moderate MAP range (West Virginia and Kentucky), and region 3 – upper MAP range (Tennessee, North Carolina, South Carolina, Georgia, Alabama, and Mississippi).

Flood count data for each county were compiled from the NCDC storm events database (SED). Floods are technically defined by streamflow events that rise above the streambanks and exceed the capacity of the stream channel. The SED contains data for weather events from 1996-present for the United States. Floods and flash floods are reported as count data (i.e., occurrence of flood) by location or county, date and time of event, magnitude, deaths, injuries, property damage, and crop damage. Our analysis was limited to the occurrence of floods or flash floods; reporting of other associated data was inconsistent across events, counties, and states.

The SED was queried for all floods that occurred during U.S. Geological Survey (USGS) water years (wy) 2000, 2001, and 2002 in all AR counties. A USGS water year is defined as October 1-September 30 for each year and is used to account for seasonal changes in water storage. These water years were selected to represent land use cover status 1 year before, during, and 1 year after the 2001 NLCD coverage. Flood occurrences during wy 2000, 2001, and 2002 were totaled for each county. A total of 1,433 storms were reported for all AR counties during the analysis period.

A generalized linear model (GLM) was developed to identify the landscape and climate attributes that explain the largest amount of variations in flood count data by county. The dependent variable, flood count, was regressed on explanatory variables thought to either mitigate or exacerbate floods. To account for skew in the flood count data (e.g., preponderance of no events in some counties when events occurred in other counties), regression models were fit by using a Poisson distribution. The Poisson distribution is important for describing random occurrences when the probability of occurrence is small. For example, an extreme event during any given year has a lower probability of occurring compared to an event closer to average conditions.

Because different landscape and climate attributes affect flooding differently (e.g., a unit area of forest and unit area of impervious surface may not mitigate or exacerbate flooding equally), each attribute was weighted based on its relative contribution in explaining variations in flood count data. Regression model slope coefficients were used to determine how each attribute affects flooding. A positive slope coefficient indicates that the attribute exacerbates flooding; a negative slope coefficient suggests a reduction or mitigation of flooding. The value of the slope coefficient describes a 1-unit change (increase or decrease) in flood response, given the slope coefficient for each attribute.
To account for the differing effects of each attribute on flooding, each explanatory variable was multiplied by the associated slope coefficient and rescaled to between 0 and 100. Rescaled attributes were then weighted to account for their relative contribution in explaining model variance. The weight of each variable was calculated by using deviance and null deviance from analysis of variance and calculated as:

$$\text{weight} = [\text{null deviance} - \text{deviance}]/\text{null deviance}$$

where null deviance is the deviance explained by the null model and deviance is the relative contribution of each variable in explaining model variance. Weights were rescaled by comparing individual weight value to the range of all weights. Rescaled attributes were then multiplied by weighting factors to produce regression-weighted attributes that either exacerbate or mitigate flooding in the AR counties.

RESULTS AND DISCUSSION

During 2000, 2001, and 2002, 1,433 floods and flash floods were reported for the 420 AR counties. Kentucky had the greatest number of floods reported with 242, followed by 230 in West Virginia, then Ohio with 191 floods. Georgia, Maryland, and South Carolina had the fewest floods reported with 10, 19, and 26, respectively. When data were normalized by area, Kentucky, Maryland, and Ohio had the greatest number of floods.

Pike County, Kentucky, experienced the greatest number of floods of all AR counties with 22 floods reported in the SED during 2000 through 2002. The large number of floods trends well with the land use. Though Pike County is largely forested (77 percent) and has minimal agriculture (0.025 percent), its topography is very steep, with average slopes of 45 percent. The county has high surface coal production per square mile (45,165 units). Similarly, Boone County, West Virginia, has a large number of floods relative to flooding in all AR counties, with 10 reported flood events. Boone County is heavily forested (85 percent) with minimal agriculture (0.01 percent), is very steep (42 percent slope), and produces approximately 64,233 units of surface coal production per square mile. Under the National Flood Insurance Program, a total of $33,358,385 has been paid to Pike County residents, $262,360,845 to Kentucky, $1,618,554 to Boone County residents, and $283,436,665 to West Virginia since 1978 on account of flooding (Federal Emergency Management Agency, N.d.).

In contrast, Unicoi County, Tennessee, reported no floods during these years. Approximately 86 percent of Unicoi County is forested and 0.02 percent is agriculture. This county has steep slopes (35 percent) and no surface coal mine production per square mile. Since 1978, a total of $108,990 has been paid to Unicoi County residents and $298,515,927 to Tennessee on account of flooding (Federal Emergency Management Agency, N.d.).

Regression analysis suggests that percentages of forest, agriculture, riparian forest, and impervious surface; precipitation; slope; and surface coal production per square mile were significant in explaining variations in flood data for AR counties. Based on this analysis, directional changes in land use and topography can increase or decrease flood count data for each county. For example, either a 0.26-percent increase in forest cover or an 18.6-percent increase in riparian forest has the potential to decrease floods by one flood count unit (Table 1). Alternatively, a 0.00001-percent increase in surface coal production or a 0.03-percent increase in topographic slope has the potential to increase flooding by one unit.

Table 1.—Results of GLM regression analysis to identify significant land use attributes for Appalachian Region counties

Coefficient	Deviance	Residual deviance	Slope Coefficient [null-dev]/null*100	Weighting	Slope coeff[a]
Null	1409.3	-	-	-	-
% Forest	8.9	1400.4	0.63	0.10	-0.26
% Ag	34.6	1365.8	2.46	0.37	1.06
% Rip For	92.3	1273.5	6.55	1	-18.6
% Imperv	4.9	1268.6	0.35	0.05	9.525
MAP region	70.5	1198.1	5.00	0.76	-0.3
% Slope	60.0	1138	4.26	0.65	0.03
coal/sq mi	7.0	1131	0.49	0.08	0.00001

[a] Slope coefficient shows directional change in unit flood count data per change in slope parameter; (-) indicates a decrease in flood response and (+) indicates an increase in flood count data.

CONCLUSIONS

Regression analysis shows how directional changes in land use and topography can increase or decrease flood count data for each county. Land use activities that reduce soil infiltration capacity, such as heavy grazing, surface mining, and heavy machinery, or that convert or remove vegetation, have the potential to increase streamflow. Such activities translate a larger proportion of precipitation to runoff, rather than allowing it to be stored in soil, and reduce the overall amount of water lost to the atmosphere through interception and evapotranspiration. Therefore, future changes in land use have the potential to increase or decrease flooding and should be considered when addressing economic development, resource management, and evaluation of AR water assets.

ACKNOWLEDGMENTS

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SOIL CHEMICAL CHANGES ON TWO FORESTED WATERSHEDS IN WEST VIRGINIA WITH TIME AND ACIDIFICATION TREATMENT

Mary Beth Adams[1]

Abstract.—Forest soil chemistry remains one of the least understood components of most ecosystem studies. This presentation describes exchangeable soil nutrient concentrations on two forested watersheds on the Fernow Experimental Forest in West Virginia. These two gauged watersheds, both containing stands of deciduous Appalachian hardwoods, form the backbone of the Fernow Watershed Acidification Study, which was initiated in 1989. Ammonium sulfate ($[NH4]_2SO_4$) fertilizer has been applied to one of these watersheds at a rate of 35.5 kg N/ ha and 40.5 kg S/ ha since 1989. The second watershed, which supports an older stand (~100 years old) of mixed hardwoods, serves as the reference watershed for this study. Soils were sampled in 1994, 2002, and 2010 and were analyzed for chemical constituents. Significant changes in soil chemical properties were not detected after 12 years of treatment, and changes in soil chemistry at 21 years were also ambiguous. Hypotheses related to soil acidification are discussed and evaluated in light of the long-term data. Ancillary data on foliar nutrients and growth rates of trees are also included in this analysis.

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GEOGRAPHIC INFORMATION SYSTEMS

COMPARISON OF LIDAR-DERIVED DATA AND HIGH RESOLUTION TRUE COLOR IMAGERY FOR EXTRACTING URBAN FOREST COVER

Aaron E. Maxwell, Adam C. Riley, and Paul Kinder[1]

Abstract.—Remote sensing has many applications in forestry. Light detection and ranging (LiDAR) and high resolution aerial photography have been investigated as means to extract forest data, such as biomass, timber volume, stand dynamics, and gap characteristics. LiDAR return intensity data are often overlooked as a source of input raster data for thematic map creation. We utilized LiDAR intensity and elevation difference models from a recent Morgantown, WV, collection to extract land cover data in an urban setting. The LiDAR-derived data were used as an input in user-assisted feature extraction to classify forest cover. The results were compared against land cover extracted from high resolution, recent, true color, leaf-off imagery. We compared thematic map results against ground sample points collected using realtime kinematic (RTK) global positioning system (GPS) surveys and to manual photograph interpretation. This research supports the conclusion that imagery is a superior input for user-assisted feature extraction of land cover data within the software tool utilized; however, there is merit in including LiDAR-derived variables in the analysis.

INTRODUCTION

Light detection and ranging (LiDAR) is an active remote sensing technology that utilizes near-infrared light pulses, differential GPS, and inertial measurements to accurately map objects and surfaces along the earth. The technology is often utilized from an aerial platform to create elevation and topographic models of the Earth's surface (Lillesand et al. 2008). It has many applications in forestry research due to the high spatial resolution and accuracy of the data and also the ability to collect multiple returns for a single laser pulse, which allows for the analysis of the vertical structure of forested areas (Wynne 2006). Forestry inventory attributes and canopy metrics such as canopy height, basal area, volume, crown diameter, and stem density have been derived from LiDAR data (Magnussen et al. 2010, Næsset 2009, Popescu et al. 2003). Also, the classification of individual tree species has been pursued (Brandtberg 2007, Ørka et al. 2009).

LiDAR intensity is a measure of the strength of the return pulse, and this measurement is correlated with surface material (Lillesand et al. 2008). However, prior research by Lin and Mills (2010) has shown that return intensity is influenced by many variables including footprint size, scan angle, return number, and range distance. LiDAR return intensity has not been as heavily explored for its usefulness in forestry and land cover mapping due to the difficulty of radiometric calibration (Flood 2001, Kaasalainen et al. 2005). Brennan and Webster (2006) explored the use of LiDAR-derived parameters, including intensity, for land cover mapping using image object segmentation and rule-based classification and obtained individual class accuracies averaging 94 percent.

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The purpose of this work was to compare LiDAR-derived data, LiDAR all return intensity and elevation difference models, and high resolution aerial imagery as inputs for user-assisted feature extraction of land cover with the software tool Feature Analyst (Visual Learning Systems, Missoula, MT). Land cover was differentiated in an urban setting and results were compared. The following land cover classes were of interest: barren/developed/impervious, grass, water, deciduous tees, and coniferous trees. We investigated whether forested land cover could be differentiated from other land cover types in an urban environment using feature extraction if only LiDAR data are available but no high-resolution imagery. The LiDAR-derived data were utilized in a raster format.

User-assisted feature extraction uses user-defined knowledge, as training data, to recognize and classify target features in an image (Visual Learning Systems 2002). Feature Analyst uses machine-learning algorithms and techniques as object recognition to automate feature-recognition from imagery (Visual Learning Systems 2002). Unlike supervised classification techniques, feature extraction classifies an image using more than just the digital number (DN) or spectral information contained by each pixel. Spatial context information such as spatial association, size, shape, texture, pattern, and shadow are considered (Opitz 2003). Studies have shown that feature extraction or object-based algorithms are more effective and accurate at extracting information from high resolution imagery than traditional image classification methods, such as supervised classification, because additional image characteristics are considered such as spatial context (Friedl and Brodley 1997, Harvey et al. 2002, Hong and Zhang 2006, Kaiser et al. 2004).

Feature extraction takes into account the spatial context that is available in high resolution data. We hypothesized that the textural information available in LiDAR-derived data could be utilized to differentiate forested land cover from other land cover types. As Figure 1 demonstrates, forested areas often show more texture and variability of LiDAR intensity values than more homogenous surfaces, such as pavement or grass.

STUDY AREA

This study was conducted in Morgantown, WV, within a 5.3 km^2 area near the Evansdale Campus of West Virginia University (Fig. 2). This area was selected because LiDAR and high resolution aerial imagery were available and a wide variety of land cover types are present.

METHODS

LiDAR Data

LiDAR data were collected on November 12, 2008, at an altitude of 3,500 ft (1066 m) above ground level (AGL) from an aircraft platform. An ALTM 3100 sensor was utilized at a pulse rate of 100 kHz, a half scan angle of 18 degrees, and a scan frequency of 30 Hz. Up to four returns were recorded per laser pulse. This was a leaf-off collection.

Imagery Data

True color imagery was flown during leaf-off conditions in March of 2010 at a cell size of 6 inches. This imagery was made available by the Monongalia County Commission. Visual inspection of the imagery showed that it was well color balanced and precisely orthorectified.

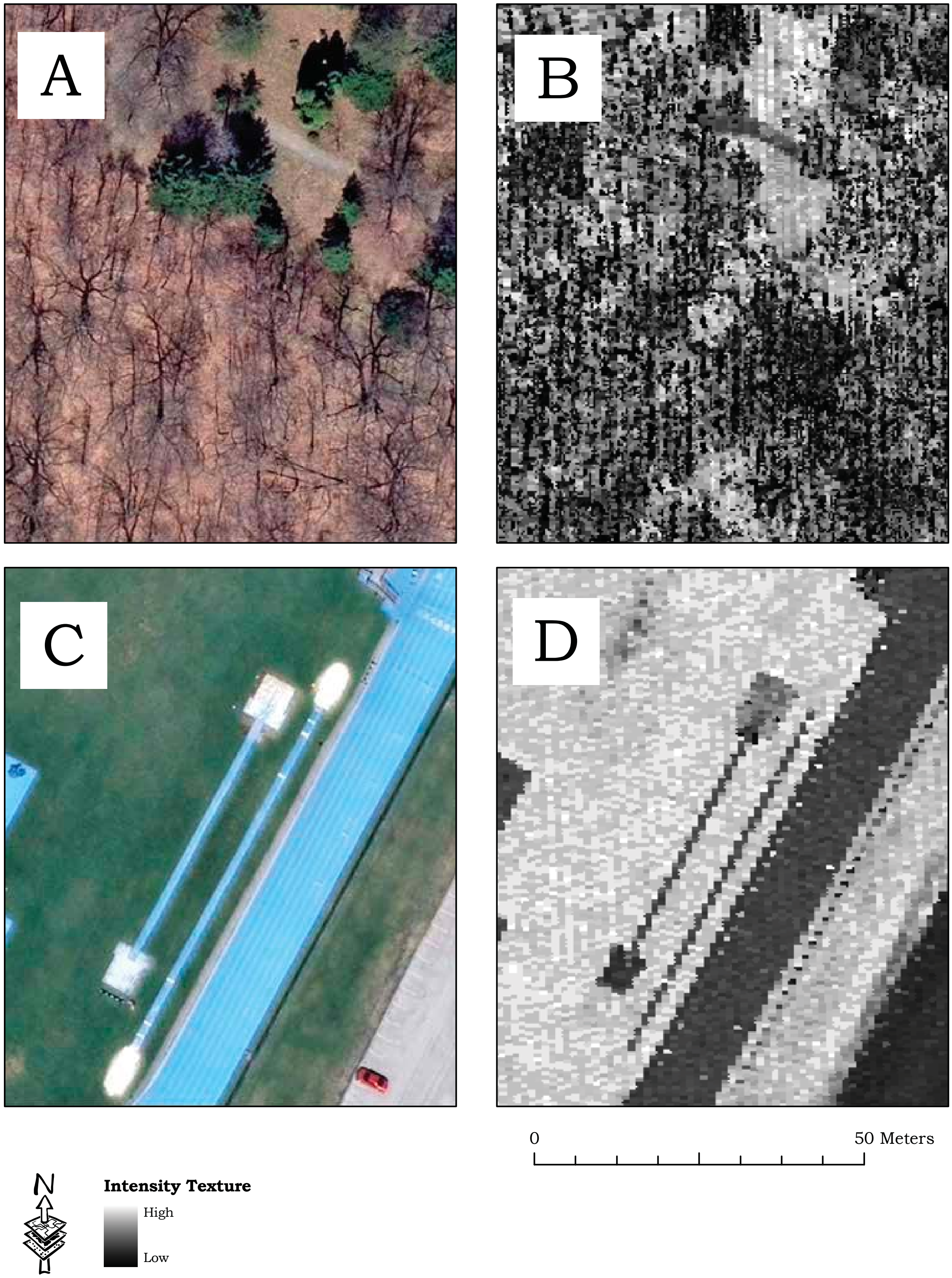

Figure 1.—Comparison of LiDAR intensity texture in forested (A and B) and nonforested (C and D) areas (1 ft cell size intensity models and 6 inch cell size imagery).

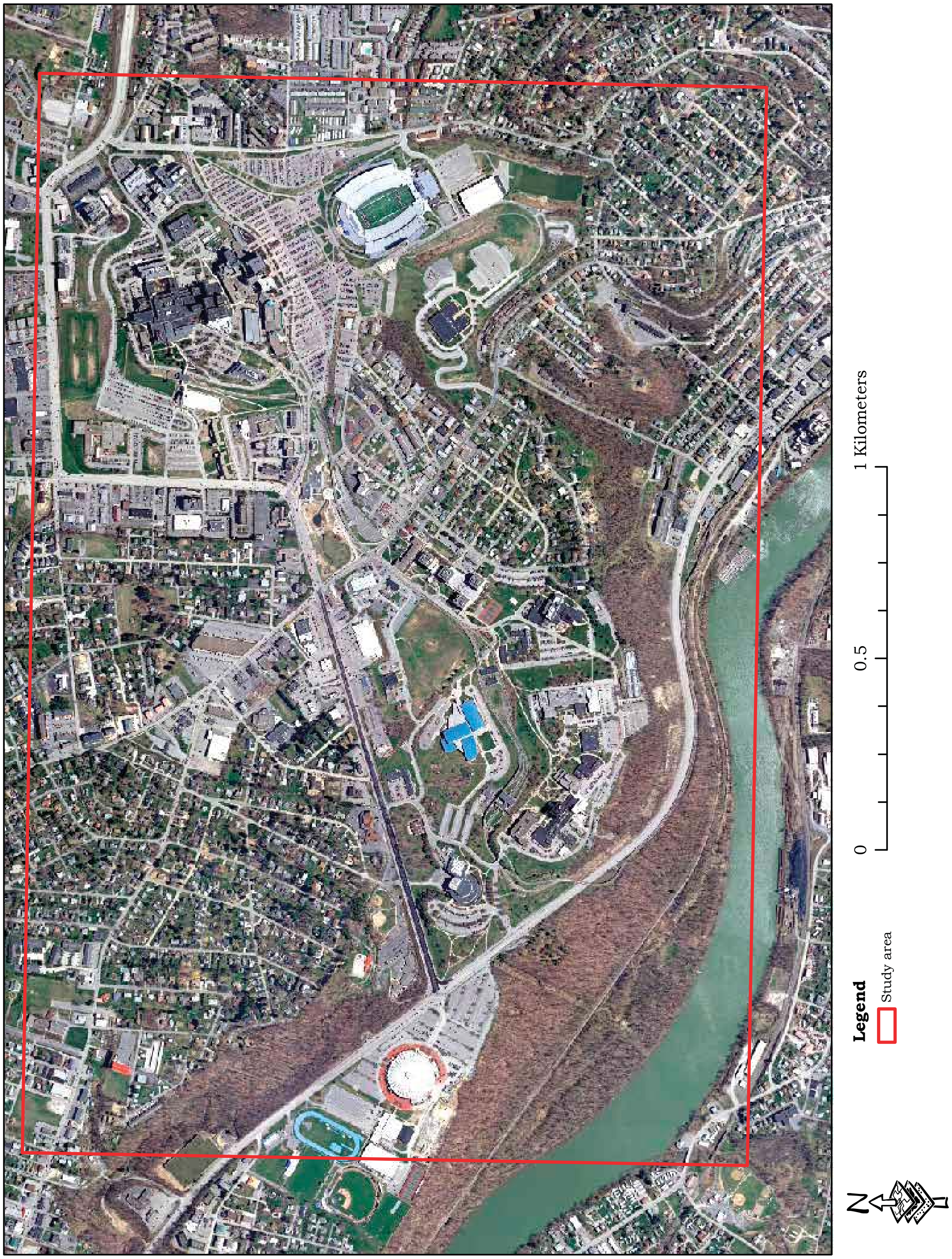

Figure 2.—Study area in Morgantown, WV.

Data Preparation

Raster grids were created from the LiDAR point data. The data were converted to multipoint shapefiles within ArcMap using the 3D Analyst Extension. Point data were then interpolated to raster grids using inverse distance weighting (IDW). Grids with a cell size of 1 ft were created for all returns and ground returns to create a digital elevation model and a digital surface model. The ground model was subtracted from the all returns model to obtain an elevation difference model for the study area.

Table 1.—Training data for land cover classes

Class	Number of training polygons	Total area
Water	60	73,505 m^2
Grass	80	12,774 m^2
Deciduous trees	55	22,923 m^2
Coniferous trees	53	1,472 m^2
Barren/Developed/Impervious	264	59,201 m^2

Table 2.—Feature Analyst parameters used

Parameter	Imagery	LiDAR-Derived	All
Classification method	Multi-class	Multi-class	Multi-class
Output format	Raster	Raster	Raster
Wall-to-wall classification	Applied	Applied	Applied
Resampling factor	2	1	1
Histogram stretch	Applied	Applied	Applied
Input presentation	Manhattan (7)	Manhattan (9)	Manhattan (5)
Find rotated instances of features	Applied	Applied	Applied
Learning algorithm	Approach 1	Approach 1	Approach 1
Aggregate areas	80	80	80

Elevation differences between the surfaces were most commonly a result of vegetation and manmade structures. An intensity grid was created from the all returns data at the same resolution using the same methodology.

Training Data

Training data for the land cover classes of interest were created by manual interpretation of the imagery and LiDAR-derived raster grids as polygons within ArcMap; as a result, land cover training data were created by visual interpretation of the input raster grids. Training data were collected throughout the study area in order to take into account class variability. Table 1 describes the training data collected. Due to variability, the most training data were collected for the barren/developed/impervious class. Separate training data were collected for conifers and deciduous trees. The same training data was used for each feature extraction performed so as not to induce variability or bias between the runs.

Feature Extraction

Three separate feature extractions were performed using the following raster data:

1) True color imagery
2) LiDAR-derived variables (all return intensity and elevation difference)
3) All three inputs

This was conducted so that comparisons could be made between thematic map results obtained from only the imagery, only the LiDAR-derived variables, and a combination of the two. User-assisted feature extraction was performed within ERDAS IMAGINE® using the software tool Feature Analyst by Visual Learning Systems. This software tool has many user defined parameters as described in Table 2.

The only parameters changed between runs were the resampling factor and the pattern width of the input presentation. The resampling factor was set at 2 for the image only result so that a 1 ft cell size output would be obtained to match the cell size of the other results. The input presentation determines the shape and size of the search window used to gather spatial context information for each pixel. Feature Analyst records the spectral information for all pixels within the pattern to define the characteristics of the land cover class. Within Feature Analyst, the number of bands multiplied by the number of pixels within the search window cannot exceed 100 (Visual Learning Systems 2002). For each run we used the maximum pattern width allowable for the Manhattan pattern to make the most use of the spatial context information in the imagery and the LiDAR-derived variables.

We defined the parameters based on results obtained in previous research, suggestions from the software user's manual, and professional judgment. Although it is possible to conduct further processing within Feature Analyst to enhance the results, we decided to compare initial outputs so as not to induce variability and bias between the runs; as a result, the final accuracies obtained here should not be considered a representation of the optimal use of the software. All results were thematic map raster grids with a 1 ft cell size.

Error Assessment

Two error assessments were performed. First, 10,000 random points were selected using Hawth's Tools, an extension for Arc Map. The thematic map class for each run was determined at each point. A 200-point subset of these points was then randomly selected for validation. We then manually interpreted the land cover class at the point locations by comparison to the true color imagery.

Second, 140 ground points were collected in the study area representing thematic categories using Pacific Crest realtime kinematic (RTK) survey equipment. The horizontal precision of these points averaged 0.03 m (3 cm). These points were then compared to the thematic map results. It should be noted that these points do not represent a rigorous random sample. They were collected to conduct a relative comparison of the mapping results and should not be considered a measure of true accuracy.

RESULTS AND DISCUSSION

Thematic map results are provided in Figures 3 through 5. By visual inspection, several observations can be made regarding the products. First, two problems associated with image classification at this spatial scale are shadowing and relief displacement of above ground objects, such as trees. In the imagery alone result, we observed that tree shadows were often classified as part of the tree, potentially overestimating the tree extents. Building shadows were often classified as coniferous trees. We generally found that the inclusion of the LiDAR-derived parameters help to reduce this type of error. An example is shown in Figure 6 in which a water tower shadow was classified as coniferous trees in the image only result but was more correctly classified in the result utilizing all variables. Relief displacement is a problem in aerial imagery, but is not a problem in the LiDAR data. This displacement distorts the true location and spatial extent of a tree crown. There were also classification errors associated with roofs, which contain spectral variability by color and texture. Generally, LiDAR data enhanced roof and building classification.

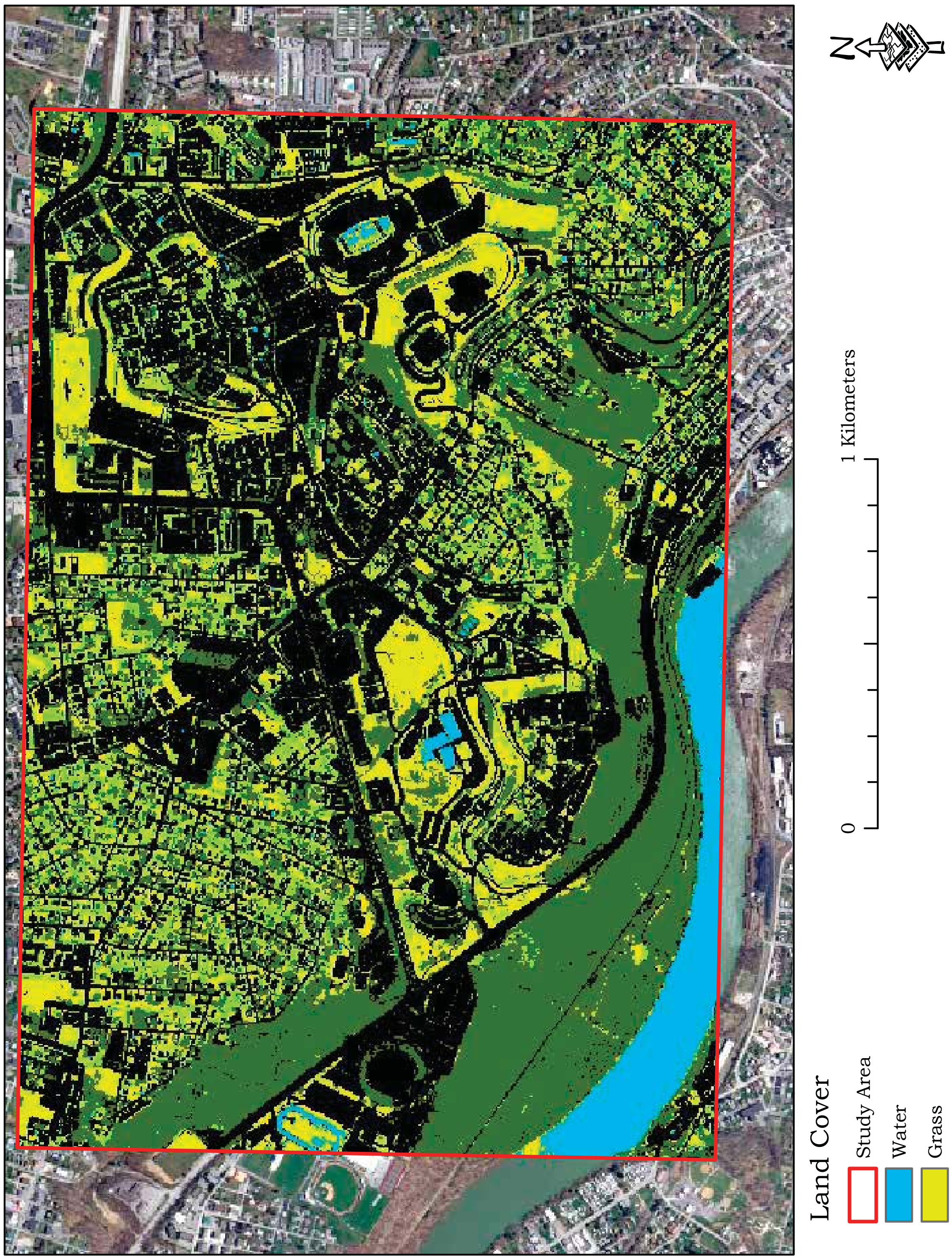

Figure 3.—Land cover result for imagery alone.

Figure 4.—Land cover result for LiDAR-derived variables alone.

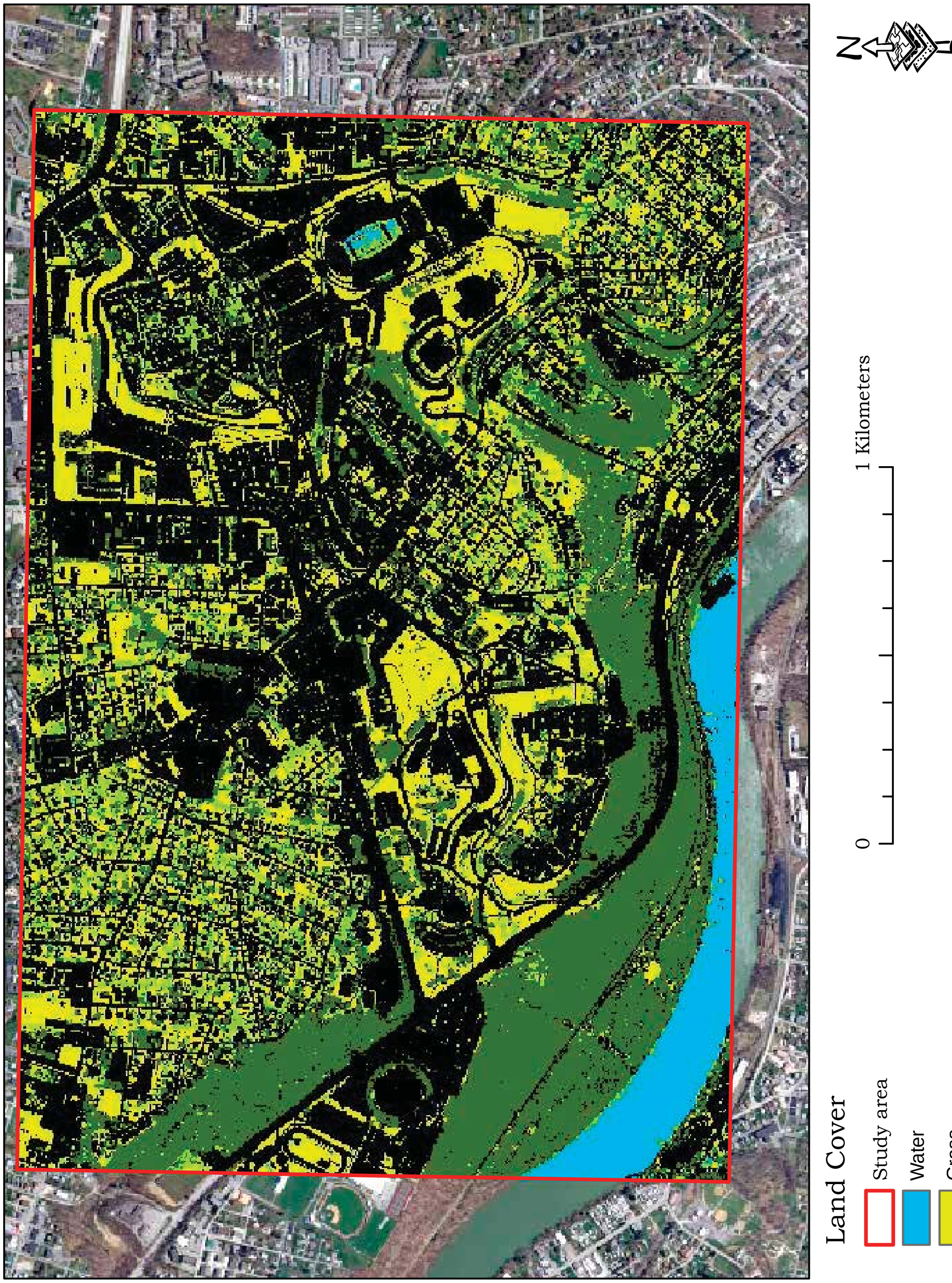

Figure 5.—Land cover result for all variables.

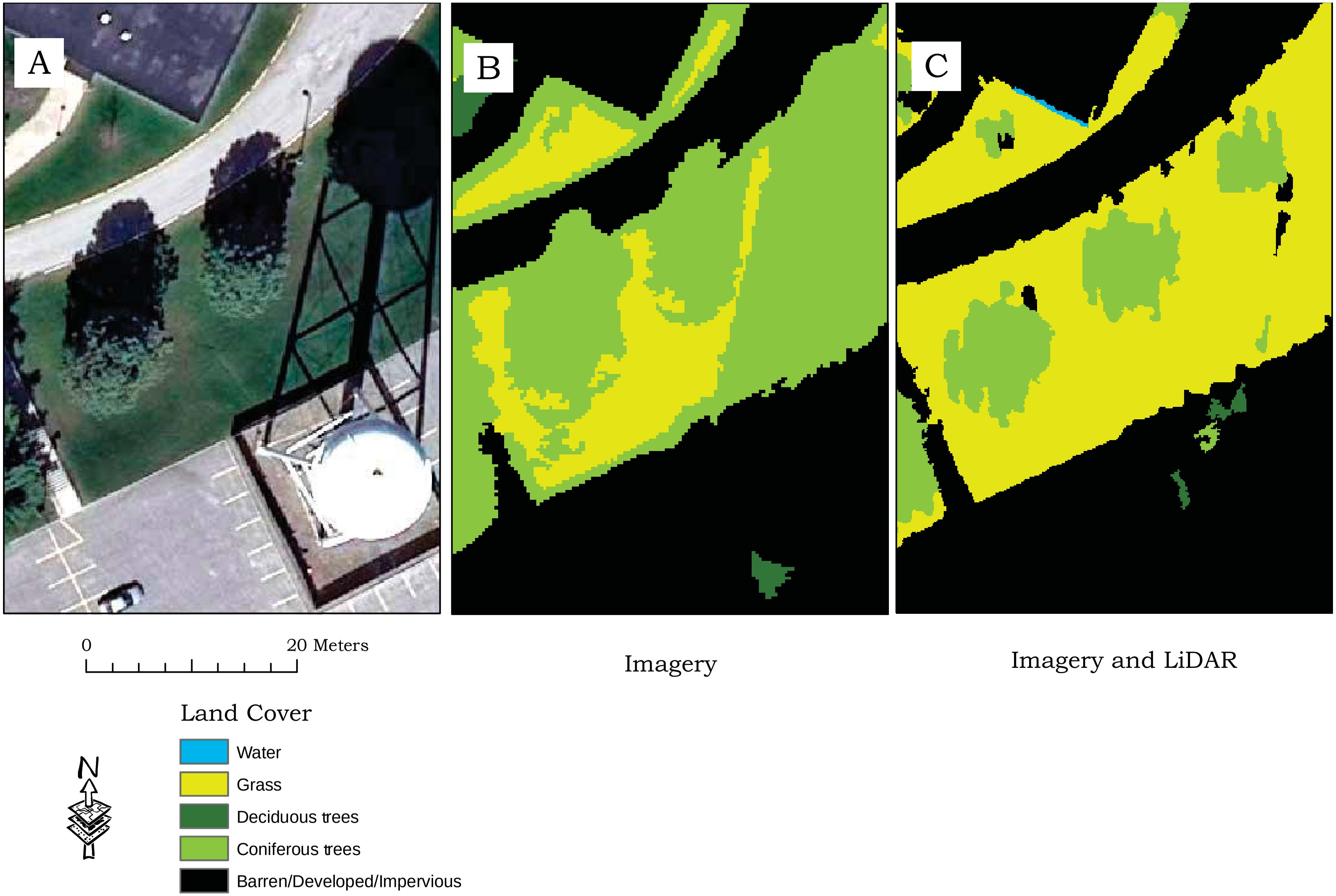

Figure 6.—Comparison of shadow classification. Land cover in shadows was more correcty classified when utilizing LiDAR-derived data along with the imagery. With only imagery, land cover in shadows was commonly incorrectly classified as coniferous trees.

LiDAR-derived data poorly separated deciduous and coniferous trees as shown in Figure 7. It should be noted that leaf-off LiDAR data were utilized, and leaf-on data were not assessed. Leaf-on data may allow for more separation between these forest types; however, that was not explored. Based on visual inspection, coniferous and deciduous trees were more accurately differentiated from imagery than LiDAR-derived parameters. This may be a result of intensity, elevation difference, and intensity spatial texture being similar for both categories. In leaf-off imagery, deciduous and coniferous trees are spectrally different. These forest types proved to be more separable using image spectral bands than LiDAR intensity and elevation difference within the software tool utilized.

Error matrixes for the classifications are provided in Tables 3 through 6. Thematic map accuracy was compared at randomly selected point locations based on manual photograph interpretation. These error matrixes suggest that the classification relying on LiDAR-derived variables alone was least accurate. Confusion between coniferous and deciduous trees was common. The matrixes and K_{hat} coefficients of agreement do not suggest a significant increase in accuracy when LiDAR-derived parameters are included with the imagery.

Error assessment relative to the ground surveyed points showed a relative increase in accuracy if both imagery and LiDAR-derived parameters were utilized as described in Table 6. Deciduous and coniferous forests were not differentiated in this assessment due to the inability to accurately sample coniferous trees with the RTK equipment. This assessment suggests that omission error, or the misclassification of tree pixels as other land cover types, was the dominant error source.

If the error matrix for the LiDAR-derived data only (Table 4) is recalculated so that error between coniferous and deciduous forest is not considered but rather a single forest class, an increase in both the user's and producer's accuracy for the forest class is observed (Table 7). If a binary forest raster is desired within an urban or developed landscape, it may be appropriate to utilize only LiDAR-derived variables in a feature extraction environment; however, if coniferous and deciduous trees are to be differentiated, imagery may be necessary.

Table 3.—Error matrix with imagery utilized

		Reference data					
		Water	Grass	Deciduous	Coniferous	Barren	User's accuracy
Classification	Water	9	0	0	0	0	100%
	Grass	0	25	0	2	1	93%
	Deciduous	0	6	39	0	10	71%
	Coniferous	1	8	0	7	2	39%
	Barren	0	1	0	0	89	99%
	Producer's accuracy	90%	62%	100%	78%	87%	Overall: 85% K_{hat}: 77%

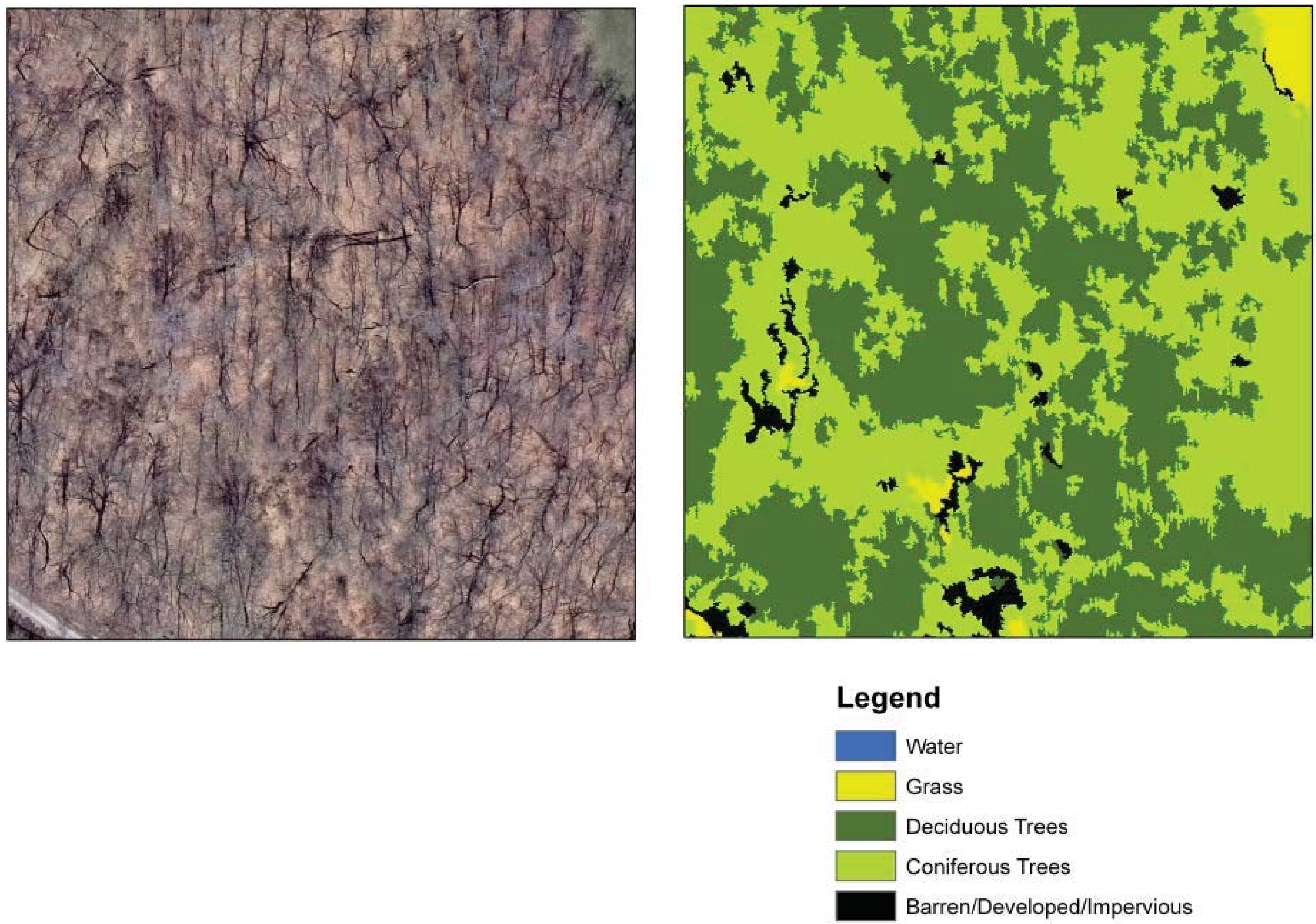

Figure 7.—Example of forest misclassification. Coniferous and deciduous trees were confused when only LiDAR-derived data were utilized.

Table 4.—Error matrix with LiDAR-derived data utilized

		Reference data					
		Water	Grass	Deciduous	Coniferous	Barren	User's accuracy
Classification	Water	7	0	0	0	2	78%
	Grass	0	33	4	0	6	77%
	Deciduous	0	0	10	0	6	63%
	Coniferous	0	4	23	9	12	19%
	Barren	3	3	2	0	76	90%
	Producer's accuracy	70%	83%	26%	100%	75%	Overall: 68% K_{hat}: 54%

Table 5.—Error matrix with all data utilized

		Reference data					
		Water	Grass	Deciduous	Coniferous	Barren	User's accuracy
Classification	Water	9	0	0	0	0	100%
	Grass	0	29	0	0	0	100%
	Deciduous	0	1	33	1	8	77%
	Coniferous	1	5	5	8	4	35%
	Barren	0	5	1	0	90	94%
	Producer's accuracy	90%	73%	85%	89%	88%	Overall: 85% K_{hat}: 77%

Table 6.—Error relative to sampled ground points

	Imagery	LiDAR-derived	All
Forest comission error	10%	0%	0%
Forest omission error	14%	25%	9%
Overall accuracy	93%	91%	97%

Table 7.—Error matrix with LiDAR-derived data utilized and tree type not differentiated

		Reference data				
		Water	Grass	Forest	Barren	User's accuracy
Classification	Water	7	0	0	2	78%
	Grass	0	33	4	6	77%
	Forest	0	4	42	18	65%
	Barren	3	3	2	76	90%
	Producer's Accuracy	70%	83%	88%	75%	Overall: 79% K_{hat}: 68%

CONCLUSIONS

Although there was not a significant increase in map accuracy when LiDAR-derived variables, such as elevation difference and all returns intensity, were considered, there was merit in including the data. For example, inclusion of LiDAR-derived variables, based on visual inspection, reduced the negative influence of shadows and relief displacement on thematic map results. However, differentiation of deciduous and coniferous forest was significantly improved by the inclusion of leaf-off imagery in the analysis. If the desired product was a binary result to differentiate forest from nonforest, it may be appropriate to utilize only LiDAR-derived data. It should be noted that the results of this analysis only apply to the software tool in question. Other processes may allow for more accurate land cover mapping, such as the methods suggested by Brennan and Webster (2006). We simply compared initial outputs using variable data inputs; as a result, it may be possible to increase thematic map accuracy by implementing additional processing available in the software.

Future research should attempt thematic map creation from LiDAR intensity data and other derived products using other software tools and processes. Also, the inclusion of additional LiDAR parameters, such as the number of multiple returns in a given area, should be explored for their usefulness in creating thematic maps. Later echoes may help isolate deciduous trees in leaf-off data. Although this work supports the importance of imagery in thematic map creation, LiDAR data may help to increase thematic map accuracy when high resolution land cover is required.

ACKNOWLEDGMENTS

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SPECTRAL REFLECTANCE OF FIVE HARDWOOD TREE SPECIES IN SOUTHERN INDIANA

Dale R. Weigel and J.C. Randolph[1]

Abstract.—The use of remote sensing to identify forest species has been ongoing since the launch of Landsat-1 using MSS imagery. The ability to separate hardwoods from conifers was accomplished by the 1980s. However, distinguishing individual hardwood species is more problematic due to similar spectral and phenological characteristics. With the launch of commercial satellites with 1-meter panchromatic and 4-meter multispectral resolution or better resolution the potential exists to distinguish individual tree crowns and thus tree species. We attempted to distinguish five hardwood tree species: American beech, black oak, sugar maple, yellow-poplar, and white oak. These five species occur commonly in southern Indiana. The spectral reflectance of single leaves from five trees of each of the five species, collected monthly from May to November, was determined using a LI-COR spectroradiometer and a specially designed spectroradiometer. We found no significant difference in the reflectance spectra of the leaves of these five species in the blue (0.45-0.52µ*m*), green (0.52-0.60 µ*m*), red (0.63-0.69 µ*m*), and near-infrared (0.76-0.85 µ*m*) wavelengths. While higher spatial resolution satellite imagery is now available, our research indicates that spectral resolution still is not sufficiently high to separate hardwood trees species.

INTRODUCTION

With the launch of Landsat-1 in 1972 there has been a continual and increasing interest in using remotely sensed images for forestry applications. Interest has ranged from differentiating the basic forest versus nonforest to the more complex species change over time. Landsat-1 was equipped with the Multispectral Scanner (MSS) with a pixel size of 79 m. Because of the large pixel size, it was not possible to distinguish individual tree species. The MSS was no longer included on Landsat-6 and later. The launch of Landsat-4 in 1982 included the Thematic Mapper (TM) with a pixel size of 30 m. The pixel size was still too large to enable separation of individual tree species.

While individual tree species could not be distinguished with MSS and TM data, forest types are distinguishable (Wolter et al. 1995); evergreen stands can be separated from deciduous stands especially if leaf-off imagery was obtained.

The launch of IKONOS by Space Imaging in 1999 marked the beginning of high-resolution commercially available satellite imagery. IKONOS imagery was available in 1-m panchromatic and 4-m multispectral resolution. Spectral resolution was similar to Landsat with blue (0.445-0.516µm), green (0.506-0.595µm), red (0.632-0.698µm), and near-IR (0.757-0.853µm) bands. Additional commercial satellites continue to be launched with ever increasing pixel resolution. GeoEye-1, launched in September 2008, had spatial resolution of 41-cm panchromatic and 1.65-cm multispectral. This increased spatial resolution provided the potential to distinguish individual tree canopies and thus the ability to identify individual tree species.

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The higher spatial resolution imagery provided the potential to distinguish individual trees species. Gougeon (1995, 2000) used a valley-following technique to delineate individual conifer tree crowns. This technique makes use of darker shaded pixels usually found between conifer trees in a stand. The darker shaded pixels are joined to form individual tree crowns. This work and that done by Wang et al. (2004) dealt with conifers, trees with easily defined crowns. However as Key et al. (2001) noted "deciduous forests appear to be a greater challenge."

Our objective was to determine whether, under controlled conditions, it is possible to distinguish from the spectral reflectance five hardwood tree species using pseudo-IKONOS images.

METHODS

Study Area

The study was conducted in 2007 on the Hardin Ridge Recreation Area (39°01'15" N, 86°27'25" W) of the Hoosier National Forest in southern Indiana (Fig. 1). The recreation area provided easy access to the open-grown tree canopies. The recreation area is in the Brown County Hills subsection of the Interior Low Plateau-Transition Hills section of the Central Interior Broadleaf Forest province (Cleland et al. 2007). The dominant forest type in the area is oak-hickory. The average annual precipitation is 43 inches spread evenly throughout the year. July has the highest average temperature, 76 °F, and January has the lowest average temperature, 27 °F.

Sampling

At each sampling date, one leaf was removed from five trees of each of five species: American beech (*Fagus grandifolia* Ehrh.), black oak (*Quercus velutina* Lam.), sugar maple (*Acer saccharum* Marsh.), yellow-poplar (*Liriodendron tulipifera* L.), and white oak (*Quercus alba* L.). These species occur commonly in southern Indiana (Leatherberry 2003). The individual trees were located throughout the recreation area (Fig. 1).

Leaves were sampled throughout the growing season from leaf-out in the spring until color change and leaf-drop in the fall. The sample dates during 2007 were May 15 and 31, July 2 and 31, August 31, September 14 and 27, and October 12 and 31. The selected leaves were all-sun leaves; no shade leaves were collected. All leaves were collected and spectral measurements made between 9 a.m. and noon on each sample date. Each leaf was photographed to provide a visual reference.

Spectral Measurements

The lower right area of each leaf was placed in a LI-COR reflectance sphere (LI-COR, Inc, Lincoln, NE). Two spectroradiometers were used to measure leaf reflectance. A LI-COR LI-1800 portable spectroradiometer measured reflectance in 2 nm increments from 350 to 850 nm. Data were recorded on a Dell laptop computer using WIN1800 software from LI-COR. The second instrument was a custom designed Omni-Spec spectroradiometer that measured reflectance in 3.3 nm increments from 350 to 1000 nm and 6.3 nm increments from 1000 to 1650 nm. Those data were recorded on a Palm Pilot. Both datasets were then exported to Microsoft Excel.

Figure 1.—Study location and trees sampled at Hardin Ridge Recreation Area, Hoosier National Forest.

Data Analysis

Using Microsoft Excel, the spectral reflectance of each leaf in each of the four bands, blue (0.45-0.52µ*m*), green (0.52-0.60 µ*m*), red (0.63-0.69 µ*m*), and near-infrared (0.76-0.853 µ*m*), was averaged into one reflectance spectra for each band creating a pseudo-multispectral IKONOS image.

Statistical analysis was performed using SAS (SAS Institute Inc., 2007) statistical software. Analysis of variance (ANOVA) was conducted by date and by band for reflectance values of the five species. Means separation between species was performed using Scheffe's multiple-comparison procedure and Tukey's studentized range test (Day and Quinn 1989).

RESULTS AND DISCUSSION

The spectral reflectance values were obtained under very controlled conditions. The light was from one direction focused at the leaf held at the same specific angle for each leaf. These conditions are quite dissimilar from those encountered under natural conditions. Under natural conditions leaves are at varying angles to the sun; sunlight may be hitting the leaves at different angles due to aspect and slope position of the tree; and leaf position within the tree affects light reflectance. However, these controlled conditions test whether it is possible to separate the five individual tree species. If it is not possible under controlled laboratory conditions, it will also not be possible under natural conditions that increase reflectance variability.

No single testing date provided a separation of the five tree species. With the LI-COR equipment, the mid- and late-May dates provided the most separation with all bands except the green band providing some separation (Table 1). But the separation tended to be one species separate from one or two with the remaining species not differing from the other species. The custom designed Omni-Spec spectroradiometer sensor only provided separation in the near-IR band (Table 2). Again it was just one species separating from another with the three other species not differing from the two species.

Table 1.—Reflectance values of four multispectral bands by date and tree species using the LI-COR spectroradiometer. For a given date and within a column, values followed by the same letter are not significantly different using Tukey's studentized range test α = 0.05.

		Blue 0.45-0.52	Green 0.52-0.60	Red 0.63-0.69	Near-IR 0.76-0.853
	Species	μm			
May 31	A beech	0.0498ab	0.1029a	0.0506ab	0.4815ab
	B oak	0.0541a	0.0985a	0.0561a	0.4878ab
	S maple	0.0479b	0.0948a	0.0473b	0.4674b
	Y-poplar	0.0501ab	0.1183a	0.0510ab	0.5007a
	W oak	0.0485ab	0.0879a	0.0459b	0.4671b
July 2	A beech	0.0484a	0.0859a	0.0489a	0.4743b
	B oak	0.0522a	0.0926a	0.0530a	0.4822b
	S maple	0.0507a	0.1066a	0.0525a	0.4712b
	Y-poplar	0.0477a	0.1005a	0.0470a	0.5095a
	W oak	0.0512a	0.0881a	0.0476a	0.4721b
July 31	A beech	0.0490b	0.0876a	0.0496a	0.4796a
	B oak	0.0516ab	0.0908a	0.0520a	0.4805a
	S maple	0.0506ab	0.0954a	0.0501a	0.4764a
	Y-poplar	0.0497ab	0.1000a	0.0500a	0.4904a
	W oak	0.0539a	0.0966a	0.0545a	0.4699a
Aug 31	A beech	0.0499a	0.0922a	0.0512a	0.4836a
	B oak	0.0512a	0.0886a	0.0520a	0.4824a
	S maple	0.0525a	0.1075a	0.0536a	0.4761a
	Y-poplar	0.0517a	0.1083a	0.0547a	0.4971a
	W oak	0.0529a	0.0861a	0.0532a	0.4721a
Sept 14	A beech	0.0511a	0.0923ab	0.0525a	0.4867ab
	B oak	0.0509a	0.0882b	0.0519a	0.4831ab
	S maple	0.0532a	0.1106ab	0.0555a	0.4830ab
	Y-poplar	0.0539a	0.1166a	0.0583a	0.5072a
	W oak	0.0539a	0.0916ab	0.0552a	0.4672b
Sept 27	A beech	0.0513a	0.0949a	0.0533a	0.4895ab
	B oak	0.0547a	0.1047a	0.0571a	0.4973ab
	S maple	0.0551a	0.1191a	0.0594a	0.4810b
	Y-poplar	0.0563a	0.1295a	0.0602a	0.5135a
	W oak	0.0539a	0.0928a	0.0534a	0.4769b
Oct 12	A beech	0.0530a	0.1023a	0.0564a	0.4882ab
	B oak	0.0538a	0.0974a	0.0559a	0.4871ab
	S maple	0.0570a	0.1259a	0.0629a	0.4854ab
	Y-poplar	0.0538a	0.1333a	0.0604a	0.5083a
	W oak	0.0561a	0.0957a	0.0566a	0.4678b
Oct 31	A beech	0.0598a	0.1888a	0.1530a	0.4830a
	B oak	0.0589a	0.1261a	0.0680a	0.4960a
	S maple	0.0704a	0.1652a	0.1484a	0.4793a
	Y-poplar	0.0648a	0.2094a	0.1394a	0.5069a
	W oak	0.0689a	0.1333a	0.0761a	0.4920a

Table 2.—Reflectance values of four multispectral bands by date and tree species using the Omni-Spec spectroradiometer. For a given date and within a column, values followed by the same letter are not significantly different using Tukey's studentized range test α = 0.05.

		Blue 0.45-0.52	Green 0.52-0.60	Red 0.63-0.69	Near-IR 0.76-0.853
	Species		μm		
May 31	A beech	0.0821a	0.1172a	0.0743a	0.5108ab
	B oak	0.0857a	0.1192a	0.0797a	0.5192ab
	S maple	0.0802a	0.1145a	0.0712a	0.4985b
	Y-poplar	0.0814a	0.1383a	0.0776a	0.5289a
	W oak	0.0813a	0.1108a	0.0727a	0.4998b
July 2	A beech	0.0803a	0.1058a	0.0735a	0.5063b
	B oak	0.0838a	0.1131a	0.0798a	0.5145b
	S maple	0.0826a	0.1266a	0.0808a	0.5047b
	Y-poplar	0.0814a	0.1263a	0.0795a	0.5403a
	W oak	0.0826a	0.1075a	0.0709a	0.5019b
July 31	A beech	0.0815c	0.1071a	0.0735a	0.5110a
	B oak	0.0852ab	0.1125a	0.0772a	0.5184a
	S maple	0.0841abc	0.1169a	0.0751a	0.5100a
	Y-poplar	0.0827bc	0.1205a	0.0740a	0.5234a
	W oak	0.0868a	0.1162a	0.0784a	0.5018a
Aug 31	A beech	0.0814a	0.1141ab	0.0767a	0.5183a
	B oak	0.0821a	0.1093ab	0.0761a	0.5130a
	S maple	0.0833a	0.1288ab	0.0775a	0.5063a
	Y-poplar	0.0836a	0.1329a	0.0798a	0.5304a
	W oak	0.0824a	0.1053b	0.0750a	0.5052a
Sept 14	A beech	0.0820a	0.1126ab	0.0769a	0.5199ab
	B oak	0.0821a	0.1088a	0.0753a	0.5176ab
	S maple	0.0839a	0.1312ab	0.0799a	0.5136ab
	T-poplar	0.0843a	0.1377a	0.0812a	0.5367a
	W oak	0.0857a	0.1133ab	0.0788a	0.5009b
Sept 27	A beech	0.0858a	0.1212a	0.0826a	0.5346a
	B oak	0.0879a	0.1269a	0.0834a	0.5358a
	S maple	0.0873a	0.1390a	0.0854a	0.5195a
	Y-poplar	0.0886a	0.1503a	0.0881a	0.5408a
	W oak	0.0872a	0.1177a	0.0793a	0.5173a
Oct 12	A beech	0.0871a	0.1276a	0.0836a	0.5339a
	B oak	0.0866a	0.1186a	0.0807a	0.5251a
	S maple	0.0901a	0.1491a	0.0882a	0.5206a
	Y-poplar	0.0865a	0.1530a	0.0834a	0.5413a
	W oak	0.0905a	0.1204a	0.0831a	0.5179a
Oct 31	A beech	0.0948a	0.2112a	0.1824a	0.5244a
	B oak	0.0951a	0.1541a	0.0982a	0.5393a
	S maple	0.1077a	0.1930a	0.1865a	0.5154a
	Y-poplar	0.0995a	0.2261a	0.1660a	0.5436a
	W oak	0.0995a	0.1501a	0.0980a	0.5288a

Reflectance, measured by the LI-COR spectroradiometer, provided only species separation in the near-IR band from leaves collected in mid-October (Table 1). Yellow-poplar separated from white oak with the three remaining species not different from the yellow-poplar or white oak. The Omni-Spec spectroradiometer was unable to differentiate any species for the two dates in October (Table 2). With leaf senescence, fall would seem to be a time when species separation would be possible. Different species begin senescence at different periods, with yellow-poplar beginning the earliest.

With the LI-COR spectroradiometer, the near-IR band was the only band with consistent species separation in six of the nine dates (Table 1). Again it was yellow-poplar separating from other species. However, the Omni-Spec spectroradiometer did not perform as well. The blue band had one date with separation, July 31; green band two dates, August 31 and September 14; and the red band had no species differentiation (Table 2). The slightly wider spectral increments of the Omni-Spec instrument, when averaged to get a single mean for each band, may result in less discrimination of reflectance values.

CONCLUSION

Our pseudo-multispectral IKONOS imagery did not provide adequate spectral separation among the five hardwood species we examined. This result suggests that current multispectral imagery cannot be used to distinguish hardwood tree species in the Central Hardwood Region.

While leaves collected in mid- to late-May provided the best samples to differentiate species, this time period is a limited image-acquisition window. The optimum time of greatest spectral differences may vary each year depending on weather and its influence on leaf development and expansion. Summer dates, with full leaf expansion and a longer image-acquisition period, had poorer spectral separation among species. The October dates had minimal spectral separation. The October time period like the May period is a limited image acquisition window being influenced by the weather.

Continued research is planned using the hyperspectral data, discriminant analysis, and additional statistical techniques. Because this was just an initial look at the hyperspectral data this continued examination using more sophisticated statistical techniques might provide useful methods to discriminate between the five hardwood species.

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HARVESTING AND UTILIZATION

IMPROVING STRAND QUALITY OF UPLAND OAKS FOR USE IN ORIENTED STRAND BOARD

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Abstract.—Past research estimates that more than 1 million tons of oak logging residues go unused in West Virginia each year. Much research has been done investigating potential products and markets for this underutilized resource. West Virginia is home to an oriented strand board (OSB) producer that consumes large volumes of small diameter, low quality round wood. However, the use of oak species is limited because of their undesirable physical properties. Much of this rejection is due to the poor strandability of oak and the production of significant volumes of fines during the stranding process. New stranding technology for improving the quality of oak strands produced for the OSB manufacturing process was investigated. The process of making OSB strands was examined to see if changes could be made to improve the quality of oak strands. Changes in cutting speed, knife angle, pocket angle, and rotations per minute improved the strand geometry and reduced the percentage of fines produced during the oak stranding process.

INTRODUCTION

More than 10 tons of logging residues per acre are left in the woods annually after harvest in southern West Virginia (Grushecky et al. 2006). An estimated 50 percent of that residue is low quality oak. If this trend is extrapolated to the whole state, approximately 1,125,000 tons of low quality oak is available each year in West Virginia. This residue represents a potential resource, but at present, no lasting market has developed for its use. Makers of engineered wood products consume large amounts of low quality logs, tree tops, and large branches. In particular, oriented strand board (OSB) is produced using lower density and underutilized hardwoods and smaller diameter softwoods that in many cases can be in the form of irregular logs (Maloney 1996, McKeever 1997).

A moderate size OSB mill can use as much as 730,000 tons of low quality logs and tree parts annually. It can be extremely difficult to procure enough timber for consumption on such a large scale. OSB mills in West Virginia use 52 or more species for their furnish. With these species, they are capable of using the same stranding setup and techniques to achieve the desired strands. However, the use of oak species is limited by the poor stranding quality of ring-porous hardwoods and the large area of the ray crossings. The impact force of the knives of a strander causes the wood to break the earlywood into very narrow strands. Narrow strands are geometrically undesirable because they lower the mechanical properties of the finished panels. Another drawback of stranding oak is the resulting higher percentage of fine wood particles produced. Fines are prone to overdrying, consume disproportionately large amounts of resin, and reduce product strength (Stiglbauer et al. 2006). These fines must be screened out of the process, hence lowering the yield from the log and driving up the cost of the finished product.

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Mechanical properties of OSB can be improved by using longer strands (Zhang et al. 1998). Suzuki and Takeda (2000) reported decreasing strand alignment with decreasing strand length. It is also known that modulus of elasticity (MOE) and modulus of rupture (MOR) increase with strand orientation parallel to the primary panel axis.

The geometry and quality of oak strands may be improved by altering processing variables such as moisture content and knife angle. In veneer production, knife angle is a critical factor in peeling a veneer block with a good surface (Spelter 1991). The stranding operation used by some OSB producing mills is similar to "peeling" veneer; therefore, knife angle is potentially a significant variable in improving the stranding of oak species. Moisture content and temperature have a plasticizing influence on wood, making it easier to peel or strand. Woodson (1979) noted an inverse relationship between tool force and moisture content.

In 2004, attempts were made at Weyerhaeuser's OSB mill in Sutton, WV, to use oak in the production process. Although the final product was able to meet commodity structural panel strength and stiffness requirements (as per Voluntary Product Standard PS2), the quality of strands was poor. The strands were typically very narrow and there was a high percentage of fines (<3⁄16 inch). The knife life (i.e., durability) was also poor with multiple knife changes needed per shift. The resulting poor knife durability, when stranding oak, would likely lead to reduced production and an increase in costs. In addition to the reduced knife durability, when using oak strands, panel density had to be increased, as compared to normal production to meet industry standards. It was not known if the necessary increase in panel density was due to the poor strand quality or the higher density of the oak species. Past research has indicated that higher compaction ratios resulted in panels with higher mechanical properties (Beck et al. 2009, Rice 1984). Higher density wood species will reduce the compaction ratio of the entire panel. Compaction ratio may be expressed as the density of the panel to the density of the wood species used. Hence the use of a higher density wood species may require a higher overall panel density to achieve the necessary pressure for bonding and compaction ratio. If oak species could be successfully used to produce OSB strands and panels, then industry in the regions where oak is abundant may benefit from the availability of a low cost resource in the form of oak logging residues. Conversely, the creation of a market for oak logging residues for use in OSB production will allow for increased consumption of an underutilized resource.

Because there is significant potential to increase the utilization rate of oak logging residues through the modification of stranding techniques, the Appalachian Hardwood Center (AHC) at West Virginia University, Weyerhaeuser Company, and Pallmann Machine Manufacturing Company in Germany undertook a study to answer the following questions:

1) Can strand geometry from oak be improved so the panel density does not have to be increased to compensate for the reduction of mechanical properties caused by short, narrow oak strands?
2) Can oak strands be produced with a reduction in the percentage of fines?

This paper reports the results of this study to determine if an acceptable strand can be produced with less fines production.

METHODS

Debarked (and immediately wrapped in plastic) northern red oak (*Quercus rubra*) and chestnut oak (*Quercus prinus*) logs were shipped from West Virginia to Pallmann in Germany to be stranded. Three logs, 6 feet in length and 10 inches in diameter, were selected and shipped for each species of oak. The red and chestnut oak from West Virginia made up the first trial samples. Additionally, a second trial was performed using white oak (*Quercus* spp.) logs that Pallmann selected in Germany. A Pallmann Lab-Ring Flaker PZUL 8–300 was used to produce strands from the oak logs. The laboratory strander used could be adjusted for different processing parameters. Specifically, different combinations of knife angle, cutting speed, and ring (i.e., pocket) angle were varied until the optimum combination was determined based on visual observations of the fines and the strand width.

In determining the best combination of the stranding variables, 40 separate combinations were investigated. Moisture content of the logs at time of stranding was approximately 35 percent dry basis. After the stranding trials in Germany, five bags of strands from each species (i.e., red and white oak) were sent back to West Virginia University. Each bag of strands weighed approximately 15 lbs. Three bags from each species group were first classified using a BM&M screen classifier containing eight size classifications. The size classifications consisted of 1¼ inches, 1 inch, ¾ inch, ½ inch, ¼ inch, 3⁄16 inch, ⅛ inch, and the pan (no holes). Next, the strand thickness was measured by randomly selecting 50 strands from the 1¼ inch tray. Finally, the average width and length weighted based on mass of sample pans were determined for the sample.

RESULTS

By reducing the cutting speed and using a very flat knife cutting angle, oak strands were successfully produced. The average strand length from the first trial, combining both the red and chestnut oak species from West Virginia logs, was 3.9 inches, while the average strand length from the second trial, using white oak from Germany, was 3.4 inches. During the stranding setup, a "scoring tip" was inserted into the knife assembly to cut the strands into the desired length. The length targeted may range from 3 to 5 inches. During this study, the scoring tips were set up to target a 4-inch strand length. The results of the two trials revealed that the final lengths of the oak strands were within an acceptable range of the target length.

The knife setup used targeted a strand width of 1 inch. The average strand width found for the West Virginia logs was 0.74 inches. Strand width for the German white oak logs was 0.73 inches. In prior stranding attempts using a typical industry strander and settings, the resulting oak strands were quite narrow, and large amounts of fines were produced (Fig. 1). Strands from this study using slower cutting speeds and flatter knife angle produced strands that were wider and longer than prior attempts at stranding oak using typical hardwood strander settings (Fig. 2). A graphical representation of the distribution of the strand geometry for the first and second trials may be found in Figure 3.

A significant finding from the stranding trial results was that, by using a slower cutting speed and flatter knife angle, a higher percentage of large strands (i.e., >1 inch wide) could be obtained and the percentages of fines could be reduced, as compared to current industrial strander settings. Specifically, in both the first and second studies, the largest concentration of strand width was in the 1-inch and larger category (Table 1). The first and second studies resulted in 67 percent and 70 percent of strands being classified in the 1-inch and greater width category, respectively. These percentages were considerably higher than the 60 percent of 1 inch and greater strand width for the oak stranded using typical industry settings. Between the two trials, a slight difference was noted in fines content. Both the first (10 percent) and second (4.8 percent) trials resulted in a much lower percentage of fines produced, as compared to the fines content (17.7 percent) of the of strands produced using typical industry settings.

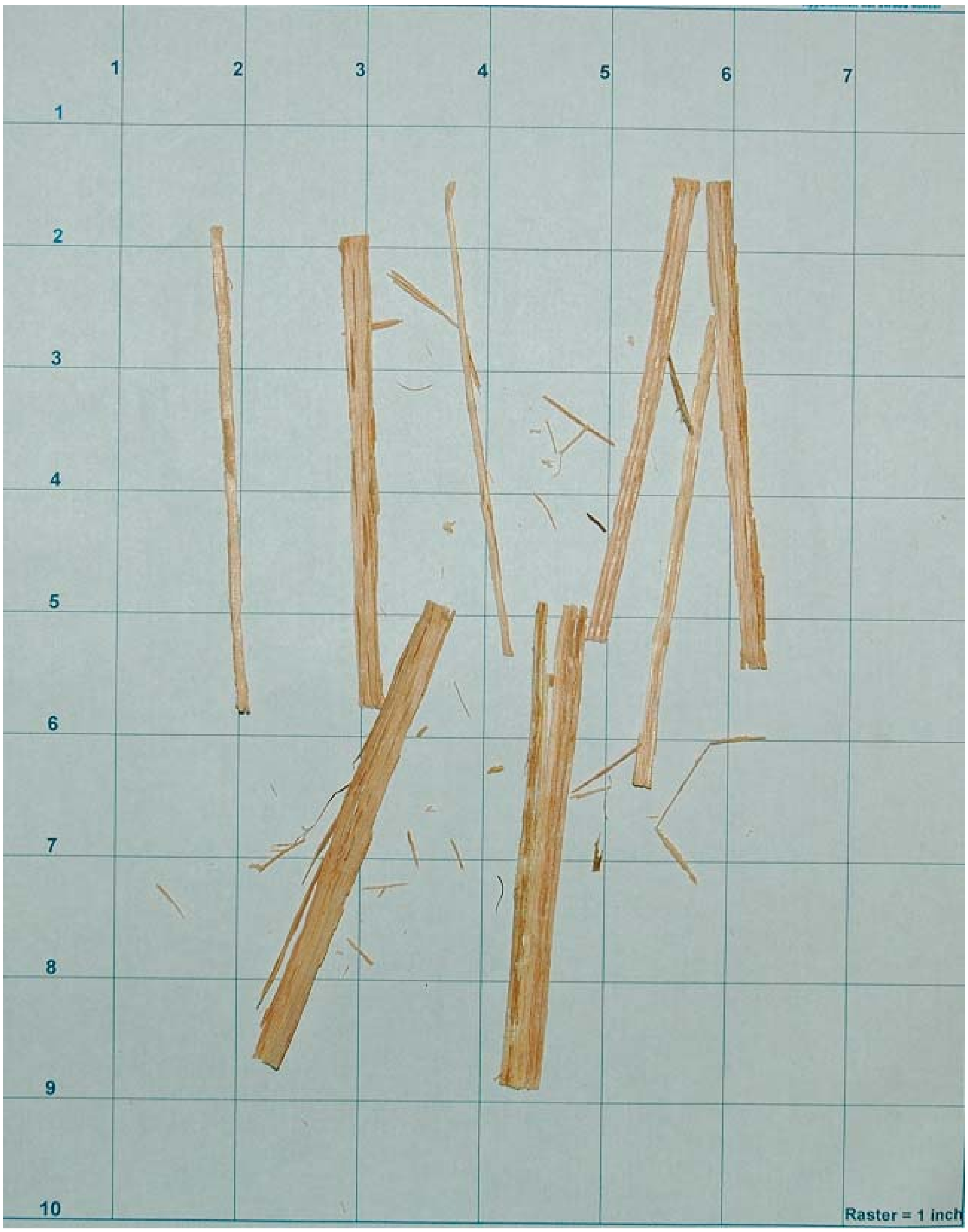

Figure 1.—Typical oak strands resulting from common strander settings.

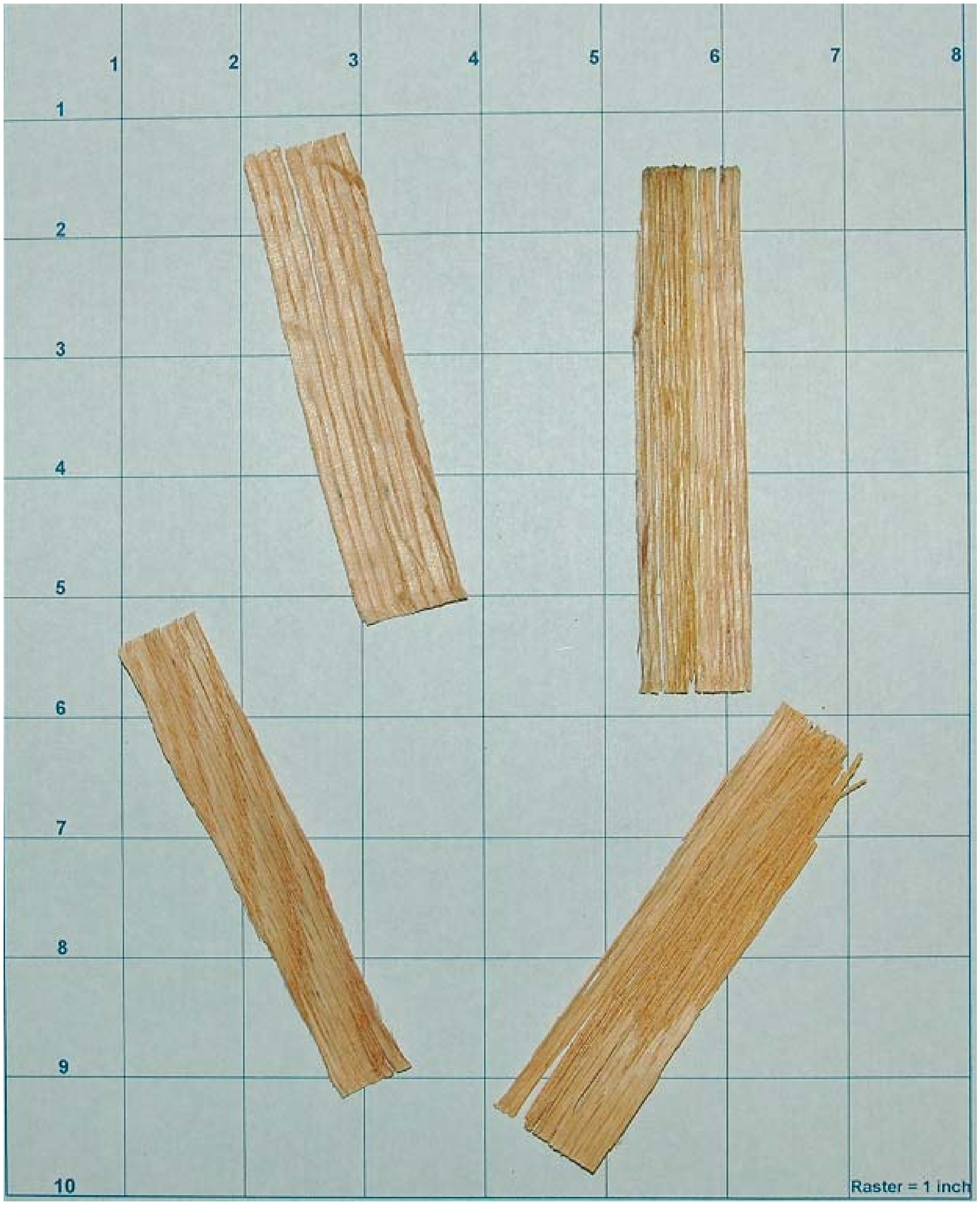

Figure 2.—Oak strands from optimized strander setup.

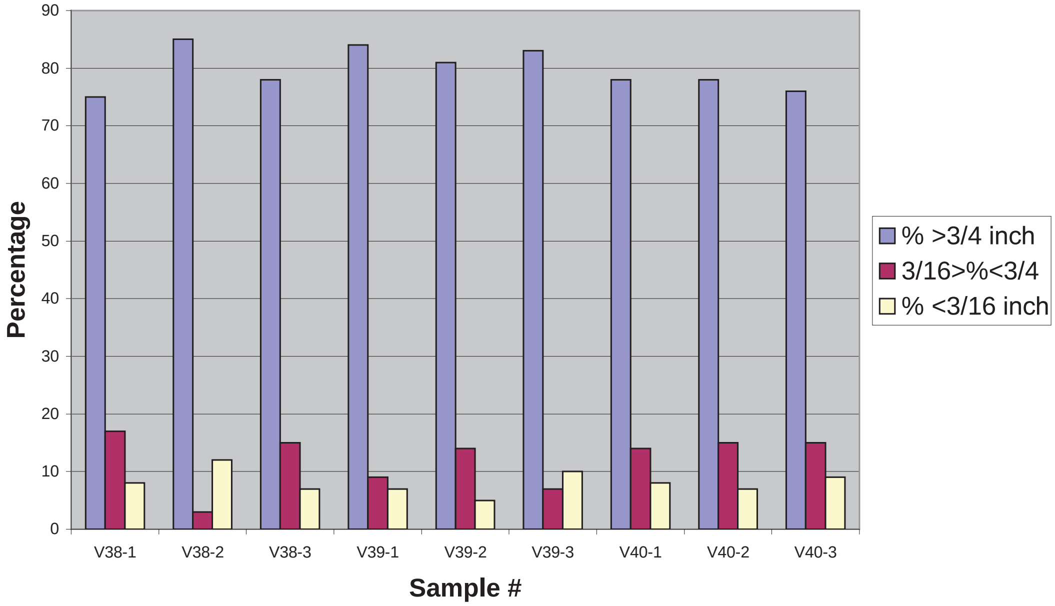

Figure 3.—Average strand width distribution for oak strands from optimal strander setup. V38, W39, and V40 represent red, chestnut, and white oak, respectively, while the -1 through 3 represent the sample log number for each species.

Table 1.—Descriptive statistics for strand data: "Length" and "Width" variables are weighted average results

Variable	n	Mean	StDev	Minimum	Median	Maximum
Oak trial 1[a]						
Length	6	3.899	0.026	3.859	3.898	3.939
Width	6	0.744	0.092	0.623	0.735	0.896
% < 3/16 inch	6	10.030	1.810	7.370	10.220	12.010
% ≥ 1 inch	6	66.940	5.040	59.820	67.680	72.400
Oak trial 2[a]						
Length	3	3.407	0.085	3.310	3.440	3.470
Width	3	0.727	0.095	0.630	0.730	0.820
% <3/16 inch	3	4.767	0.643	4.300	4.500	5.500
% ≥ 1 inch	3	70.333	1.528	69.000	70.000	72.000
Typical strands[a]						
Length	9	2.960	0.291	2.650	2.830	3.630
Width	9	0.490	0.154	0.350	0.440	0.870
% <3/16 inch	9	17.740	2.827	8.590	10.730	16.250
% ≥ 1 inch	9	59.920	10.075	40.620	62.110	70.560

[a] Oak trial 1 included red and chestnut oak sourced from West Virginia, Oak trial 2 included white oak sourced from Germany, and Typical strands included red and chestnut oak from West Virginia stranded at an OSB mill using settings for typical mixed hardwoods.

DISCUSSION

The weighted average length of 3.9 and 3.4 inches and width of 0.74 and 0.73 inches in the first and second trials, respectively, are comparable to the weighted average of the typical mixed hardwoods produced industrially. For example, mixed hardwood strands from Weyerhaeuser's mill in Sutton, WV, were found to have a weighted average length after drying of 3.10 inches and a width of 0.56 inches. The results from the Pallmann trial runs appear to have produced strands better suited for OSB production, as compared to the mill trial results. It should be noted, however, that Pallmann strands were dried in a conveyor system, while the mill strands passed through a rotary drier that could have further reduced the mill's strand dimensions. Specifically, a rotary dryer would tend to break up the strands as they tumble through the two triple-pass dryer drums. However, the oak strands were loaded by hand into bags, boxed, and air freighted from Germany. Any damage that occurred in handling of the Pallman stranded material is unknown.

The fines content from the strands produced by Pallmann was encouraging, when compared to the mill's typical fines content. A typical mixed hardwood mill would normally have 15 percent to 25 percent of fines after the stranding and before drying, with an average of about 19 percent, by weight. The oak fines content of 10 percent and 4.8 percent in the first and second trials, respectively, was found to be a noticeable improvement, as compared to the 17.8 percent fines for the oak stranded at the OSB mill using typical mixed hardwood stranding settings. The fines content results are directly comparable because both were taken after stranding before screening and drying; therefore, no damage would have been incurred on the fines before measurement.

While the strands produced in this study were comparable to typical strands used in mixed hardwood OSB mills, more research is needed to look at adding the oak strands in varying proportions in OSB panels. Specifically, research is needed to determine whether oak can be incorporated into OSB panels and maintaining mechanical and physical properties without increasing the density. Specifically, higher density oak strands will weigh more than most of the other mixed hardwood species typically used in OSB mills, so a lesser number of strands will be needed when using various portions of oak, to achieve the same overall panel density. Additionally, having fewer strands in the panel will likely reduce surface to surface pressure that is required for optimal glue bonding. However, additional research should be able to find an optimal panel density and proportion of oak strands that will produce OSB panels with mechanical and physical properties equal to that of currently produced OSB.

CONCLUSIONS

The quality of the strands produced by Pallmann, in terms of fines and weighted average length and width, is quite promising when compared to the mill's typical strand data. By slowing the cutting speed and reducing the knife angle (i.e., very flat angle), oak logs were able to be used to make strands comparable to what is typically used in OSB mills that use other mixed hardwoods. The results of the research have provided strands suitable for further investigating the addition of varying proportions of oak strands in OSB panels.

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AN INTEGRATED 3D LOG PROCESSING OPTIMIZATION SYSTEM FOR SMALL SAWMILLS IN CENTRAL APPALACHIA

Wenshu Lin and Jingxin Wang[1]

Abstract.—An integrated 3D log processing optimization system was developed to perform 3D log generation, opening face determination, headrig log sawing simulation, flitch edging and trimming simulation, cant resawing, and lumber grading. A circular cross-section model, together with 3D modeling techniques, was used to reconstruct 3D virtual logs. Internal log defects (knots) were depicted using a cone model with apex at the central axis of the log. Heuristic and dynamic programming (DP) algorithms were developed to determine the best opening face, primary log sawing, edging and trimming, and cant resawing optimization. The National Hardwood Lumber Association (NHLA) grading rules were computerized and incorporated into the system for lumber grading. The system was tested using field data collected at two central Appalachian hardwood sawmills. Results showed that lumber value recovery can be significantly improved by using the optimization system. The optimization system can assist mill managers and operators in efficiently utilizing raw materials and increasing their overall competitiveness in the ever-changing forest products market.

INTRODUCTION

Hardwood lumber production consists of a sequence of interrelated operations, including log debarking, primary log breakdown at the headrig, cant resawing, and flitch edging and trimming at the secondary log breakdown phase, as well as lumber grading. These processes are complicated due to variations in log geometry, log quality, sawing variation, sawing method, edging and trimming method, and product mix. Given this, it is extremely difficult for an operator to make an optimal sawing, edging, and trimming decision. Currently, the hardwood industry in central Appalachia is facing a set of challenges including low log quality, limited resource availability, tightened environmental restrictions on timber harvesting, reductions in profit margin, and pressure from foreign competition (Milauskas et al. 2005). Log breakdown practices in this region rely on manual inspection for external log defects, and logs are sawn to either maximize volume or lumber grade (Lee et al. 2001, Zhu et al. 1996). Similarly, edger and trimmer operators visually examine board surfaces and then make quick judgments about the placement of cuts during secondary log breakdown. These practices resulted in low lumber yield, inadequate lumber quality with respect to grade, slow production, and inefficient use of forest resources (Regalado et al.1992a). In response to these issues, there is a growing need for an advanced sawmilling technology that can optimize hardwood lumber recovery and help increase business competitiveness and profitability (Sarigul et al. 2001, Zhu et al. 1996).

Since the 1960s, several computer simulations and mathematical programming models have been developed to improve lumber recovery. For example, the Best Opening Face System (BOF) was developed to maximize the lumber volume produced from small-diameter softwood logs (Hallock et al. 1971, 1976; Lewis 1985). This program was the most widely adopted simulation model during the 1980s, and some softwood sawmills still use it today. However, the application of this program

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was limited in hardwood sawmills. Computer simulation programs were developed for hardwood log sawing (Adkins et al. 1980; Richards 1973, 1979, 1980) in which a log was represented by a truncated cone and each knot was simulated as a cone with its apex of 24 degrees at the pith. Occeña and Tanchoco (1988) developed a graphic log sawing simulator to automatically perform hardwood log breakdowns. Several studies were also conducted to analyze the impacts of sawing methods, internal defects, and log orientations on the potential lumber value recovery (Chang et al. 2005; Guddanti et al. 1998; Harless et al. 1991; Occeña et al. 2000, 2001; Steele et al. 1993, 1994).

Mathematical programming has been extensively used to achieve optimum sawing patterns. The log sawing optimization problem can be defined as a dynamic programming problem, and recursive equations were established to find the optimum total lumber value/volume recovery (Bhandarkar et al. 2002, 2008; Faaland and Briggs 1984; Geerts 1984; Todoroki and Rönnqvist 1997, 1999). Occeña et al. (1997) and Thawornwong et al. (2003) also designed the heuristic algorithm to optimize log sawing patterns. A computer-based exhaustive enumeration procedure was developed to achieve the optimal edging and trimming solution and analyze the effect of defects on lumber value (Regalado et al. 1992a, 1992b). Todoroki and Rönnqvist (1997) indicated that the edging and trimming optimization problem could be formulated as a set packing problem and be solved using dynamic programming. They developed a sawing simulator to implement the dynamic programming algorithm. Schmoldt et al. (2001) used branch-and-bound (B&B) search to obtain optimal edging/trimming solutions. To date, several edging and trimming computer software systems have been developed to aid in milling operations (Abbott et al. 2000; Araman et al. 1996; Kline et al. 1990, 1992; Lee et al. 2003; Schmoldt et al. 2001).

Decisions made in sawing, edging, and trimming operations are interrelated. For example, any decisions made in primary log breakdown directly impact the piece dimensions and the decisions in secondary log breakdown (Zeng 1991). Therefore, it is necessary to simultaneously optimize the primary and secondary breakdowns to achieve a global optimal solution. Faaland and Briggs (1984) combined primary log sawing and tree bucking using dynamic programming and modeled a log as a cylinder without taper, curvature, and defects. Geerts (1984) used a nested 2D dynamic programming algorithm to determine the optimal log sawing and flitch edging patterns. Log models and defect cores were assumed as perfect cylinders in this algorithm. Funck et al. (1993) developed a computer program called SAW3D to optimize log breakdown, edging, and trimming operations, in which only the external profile was used to represent logs. Zeng (1995) further refined this program by including internal defects and an expert system for softwood lumber grading. Todoroki et al. (1999) developed a model that integrated primary and secondary log breakdowns based on dynamic programming principles, and the combined model was incorporated into the AUTOSAW sawing simulation system (Todoroki 1997), which is appropriate only for live-sawing practices.

Existing computer simulations or mathematical programming models for log breakdown optimization differed significantly in terms of sawing method (live sawing, grade sawing), log model assumptions (truncated cone, cylinder, cross section), internal defects consideration, local optimization (primary sawing) vs. global optimization (combined sawing and trimming), and hardwood vs. softwood. Some sawing or edging and trimming systems currently used in softwood mills are not suitable for small hardwood sawmills due to the inability of considering internal defects or relying on expensive scanners (CT scanners) to detect internal defects. The log models applied were simple (cylinder or truncated cone), which created significant differences before the computer simulations were conducted. Most previous studies focused on either primary log breakdown or secondary breakdown, rather than simultaneously combining them to optimize lumber recovery. Although a few studies combined primary and secondary breakdowns for softwood or hardwood live sawing, application in hardwood sawmills, which typically use grade sawing, was limited.

Currently, most large softwood and hardwood mills have the latest sawing and optimization technology to increase lumber yield and value. Smaller sawmills, however, are less able to adopt new, more efficient technologies because of initial cost, payback period, and modifications to operations (Occeña et al. 2001). For example, only 35 percent of all Pennsylvania hardwood sawmills use a computer-aided headrig (Smith et al. 2004). In West Virginia, approximately 68.5 percent of the hardwood lumber sawmills produce less than 4 million board feet (MMBF) of green hardwood lumber per year (West Virginia Division of Forestry 2004). These small hardwood producers are key contributors to the industry because they represent a significant share of the market. Application of an appropriate, user friendly, and efficient computer-aided sawing, edging and trimming, and grading system could be one of the important strategies to improve processing performance and enhance producer competitiveness in the forest products market. Such a system is especially important in the current turbulent economic situations.

Therefore, we aim to develop a cost effective computer-aided log sawing simulation system for lumber manufacturing to improve lumber value recovery. Specifically, the objectives of this study were to (1) design a heuristic procedure to determine the log opening face based on log shape and external defects, (2) develop heuristic and dynamic programming (DP) algorithms for primary log breakdown, (3) formulate exhaustive search and DP algorithms to optimize flitch edging and trimming, (4) integrate the primary and secondary log breakdown optimization simultaneously, (5) develop an integrated 3D log processing system to implement these optimal algorithms, and (6) compare the lumber values generated in sawmills and by the optimization system.

SYSTEM DESIGN

System Components

The system was developed using the Microsoft Foundation Class (MFC) and Open Graphics Library (OpenGL). MFC provides a user friendly interface and can be easily transferred to any other Windows applications, while OpenGL offers great power to create a 3D virtual simulation environment (Wang et al. 2009). A component object model (COM) was used to integrate the system that was designed using the principle of object-oriented programming (OOP). The system consists of six major components: 3D log generation, opening face determination, headrig log sawing, flitch edging and trimming, cant resawing, and lumber grading (Fig. 1). Each component accomplishes its own task and is linked to related components by transferring arguments and/or global variables, which will make modifications and maintenance easier.

The 3D log generation component generates a 3D visual real-shape log that can be rotated, scaled, and translated based on log data and performance requirements. The opening face component determines the log position, opening face position, and opening face size. The headrig optimization component saws the log into slabs, flitches, and/or cants, and determines the optimal sawing

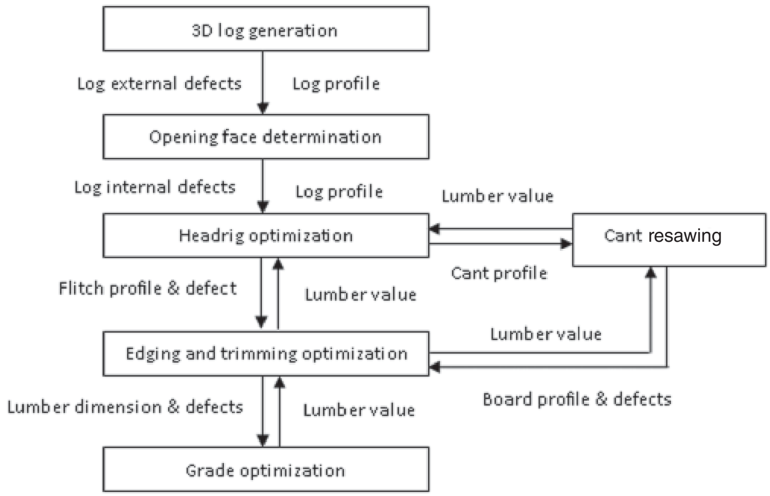


Figure 1.—System components.

patterns with maximum log value by applying either heuristic or DP algorithms. The optimum value of each flitch or cant cut from the log can be determined as well. If cant resawing is performed, the boards generated from the cant also need to be edged and/or trimmed. The edging and/or trimming optimization component calls the headrig optimization or cant resaw component for flitch/board information and defect profiles exposed on the board faces. The optimal edging and/or trimming patterns are then determined by either an exhaustive search or the DP algorithm. All the generated lumber will be processed by the lumber grading component for grading. Based on lumber dimensions, defects, lumber price, and species, the optimum lumber value will be obtained. Finally, the total lumber value, along with the corresponding optimum sawing and edging and/or trimming pattern, will be recorded in the system.

System Data Management

Microsoft ActiveX Data Objects (ADO) was used to retrieve data from and save sawing results to an MS Access database. The simple way to incorporate ADO into programming is through the use of ActiveX controls, so the user can link the system database conveniently by MFC and ActiveX controls. The MS Access database, which includes four entity types (logs, shapes, defects, and grades), was created to hold the log and lumber information in the system. The logs entity type stores log number and basic log information, such as species, log position, log length, small-end and large-end diameters; the shapes entity type stores log sweep and diameter data at 1-foot intervals; the defects entity type contains defects data associated with each log; and the grades entity type stores lumber grading rules and lumber price. An entity-relationship (ER) model was implemented via the MS database.

3D Log and Internal Defect Modeling

Log shape modeling is very important in determining the optimum log breakdown. A circular cross-section model was adopted to represent a log, which uses a series of cross sections at designated intervals along the log length (Fig. 2a). This model is much closer to real log shape because the data at each cross section were collected as well as log sweep and log crook. 3D modeling techniques, together with OpenGL primitive drawing functions, were used to generate 3D log visualizations. The OpenGL functions such as translation, rotation, and scaling are used to facilitate log visualization

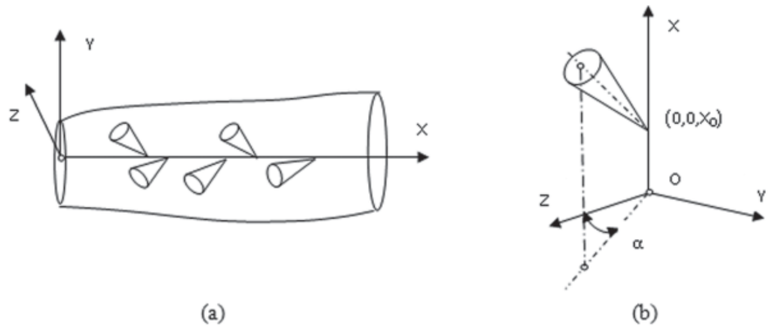


Figure 2.—3D log and defect model. (a) 3D log and knots; (b) knot represented as a cone arbitrarily positioned in the XYZ space.

and the related mathematical modeling was described by Woo et al. (2000). Studies have shown that a strong correlation exists between surface defect indicators such as overgrown knot, overgrown knot cluster, sound knot, and unsound knot and internal knot defects (Thomas 2008). We considered only knots as internal log defects in this study, because they are the most commonly found on board surfaces and can have significant impacts on log quality and lumber value. A cone model is used to represent an internal log knot with apex assumed at the central axis of the log (Thomas 2008) (Fig. 2b). The vertex of the cone lies on the X axis at a distance x_0 from the origin of the coordinates, and α is the knot angle between the Z axis and the projection of the knot axis on the YZ plane. When a sawing plane passes through an internal knot, a 2D rectangular defect area is assumed to be exposed on the lumber surface. The approximate location and size of the defect area are determined using mathematical procedures.

Determining Opening Face

During lumber production, the first cut determines the remaining cuts, which must be either parallel or perpendicular to the first cut. Therefore, the initial saw cut has direct impact on the lumber grade and volume yield (Denig 1993). In this study, the opening face is determined with consideration of log surface defects and log profile. Because no logs are absolutely straight, log sweep is considered to describe the curvature of a log. If a log's sweep is less than 3 inches, the log will be treated as a non-sweepy log; otherwise it will be deemed a sweepy log and log sweep is considered in the modeling process.

Non-Sweepy Logs

Three steps are needed to determine the opening face for non-sweepy logs (Lin et al. 2010): log orientation, best face, and opening face dimension. To maximize lumber value, a log is positioned so that defects are placed at the edge of the sawn flitch face and can easily be cut off. A mathematical procedure has been developed to identify four log faces after placing major defects at edges of the cutting planes or in one log face. It is assumed that the best face is the opening face. To determine which log face is the best, the four log faces are graded based on a computerized log grading algorithm using the U. S. Forest Service log grading rules. After the best log face is identified, the opening face dimension is then determined. The size of the opening face has a direct bearing on profitability (Denig et al. 2005). The width is the only consideration because the lumber length is assumed to be the same as the log at primary log sawing. The width of the opening face is determined using a modified version of Malcolm's opening face heuristic (Malcolm 1965). The opening face determination was described in detail by Lin et al. (2010).

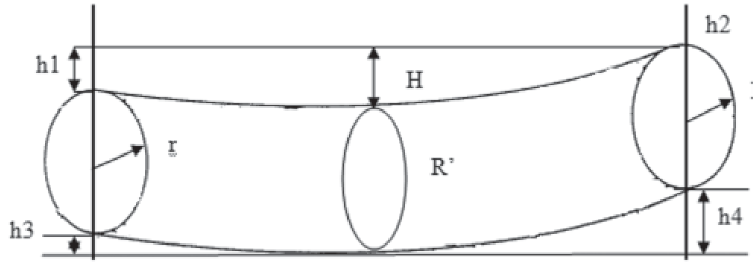


Figure 3.—Log sweep measurement.

Sweepy Logs

For logs with sweep of 3 inches or more, the opening face is based on log sweep rather than clear face (Denig et al. 2005, Malcolm 1965). It is assumed that the concave surface of a log is toward the sawyer, and log sawing starts from this face. Only one cut is allowed in this face, and then a flat surface running the full length of the log is produced. We used a no-taper sawing method with the initial lumber width at the largest sweep deviation set at 3.25 inches (3 inches is the minimum width for a validated lumber grade board and 0.25 inches is for log sawing kerf width and lumber shrinkage). The opening face widths at the small end and large end of the log are determined as in equation (1):

$$\begin{cases} w_1 = 2 * \sqrt{r^2 - (r - (H - h_1) - (R' - \sqrt{(R')^2 - 1.625^2}))^2} \\ w_2 = 2 * \sqrt{R^2 - (R - (H - h_2) - (R' - \sqrt{(R')^2 - 1.625^2}))^2} \\ w_3 = 2 * \sqrt{r^2 - (r - ((h_4 + R - \sqrt{R^2 - 1.625^2}) - h_3))^2} \\ w_4 = 2 * \sqrt{R^2 - (R - ((h_3 + r - \sqrt{r^2 - 1.625^2}) - h_4))^2} \end{cases} \quad (1)$$

where w_1 and w_2 are the opening face width at small and large end of a log, respectively, r and R are the radius of small end and large end of the log, respectively, h_1 and h_2 are the distances from the horizontal line to the small end and large end of the log, respectively, H is the maximum curved height, and R' is the corresponding log radius (Fig. 3). After the first cut, the log is rotated 180 degrees to saw the opposite side. It is also assumed that currently only one cut is produced from this face with full log length. Similarly, no-taper sawing is used and the opening face width at one log end equals 3.25 inches depending on which end has larger curve. Let w_3 and w_4 be the opening face width at small and large end of the log, respectively, when the log rotates 180 degree from the first opening face, and h_3 and h_4 be the lower height at small end and large end of the log to the ground, respectively. If $h_4 > h_3$, the opening width at the large log end will be 3.25 inches and the opening width at the small end is computed as w_3 in (1), otherwise the small end opening width will be 3.25 inches and the large end width is computed as w_4 in (1). Once the sweep has been removed from a log, the turning rules and procedures of the log would be the same as for non- sweepy logs during grade sawing process.

Primary Log Sawing Algorithms

The integrated primary and secondary log breakdown optimization is solved by linking two recursive relationships. The primary log breakdown produces a flitch that is sent to the secondary breakdown to determine the value. An optimal edging and/or trimming solution is then generated for the produced flitch. Specifically, once the log opening face is determined, the system uses either heuristic or DP algorithms to achieve the optimum sawing pattern at the headrig. The generated flitches are then edged and trimmed using the optimal edging and trimming algorithms. The optimum value of a flitch is then returned to the headrig log sawing, and the log sawing pattern is finalized.

Heuristic Algorithm

Heuristic refers to experience-based techniques for problem solving. It is more easily adaptable to a complex restriction problem, such as the log grade sawing process. In this study, the heuristic for log sawing is developed based on a modified Malcolm's (1965) simplified procedure for lumber grading from hardwood logs. The basic principle is that the log is not rotated unless one of the other log faces could yield a higher grade of lumber than the current sawing face or the current face reaches the central cant. Then the log is rotated to the next face with a potential for the highest lumber grade. This sawing process is repeated until a specified size cant is produced.

Dynamic Programming Algorithm

The primary log breakdown problem can be easily solved using dynamic programming, which separates a large problem into a series of tractable smaller problems. The key to dynamic programming is to find the recursive relationship. If lumber thicknesses, sawing kerf width, and sawing resolution were given, the recursive function for log grade sawing can be expressed as equation (2), which is a modified recursive function based on Bhandarkar et al. (2008).

$$v^*(i+1) = \max_{j\in[1,m]}\left(v^*\left(i+1-\frac{T_j}{c}-\left\lceil\frac{K}{c}\right\rceil\right)+g\left(i+1-\frac{T_j}{c}, i+1\right)\right) \quad (2)$$

where $T_j = (T_1, T_2, \cdots, T_m)$ is a set of lumber thicknesses, and m is the total number of lumber thickness, c is the sawing plane resolution (4 mm in this study), K is the kerf thickness (mm), $v^*(i)$ represents the optimal lumber value between cutting planes 1 and i, $g(i, j)$ is the lumber value from the sawing line i through j, depending on flitch edging and trimming optimization.

Flitch Edging and Trimming

Flitches produced during primary log breakdown need to be edged and trimmed to remove excessive wane and defects. The edging lines move along the vertical direction and trimming lines move along the horizontal direction of a flitch. In hardwood sawmills, edging and trimming operations occur independently, and each individual process can be optimized using mathematical algorithms. In addition, the combined edging and trimming optimization might be complex and costly, so it is of interest to optimize edging and trimming independently. For edging only, an optimal strategy is to determine the optimal spacing between the mutually paralleled edging lines so as to maximize the value of the resulted edged flitch. Similarly, for trimming only, the optimal spacing between trimming lines should be determined. Because edging and trimming operations are interrelated, the placement of edging lines has an effect on the trimming decision and vice versa. The two operations must be considered simultaneously to achieve the global optimal lumber value recovery. In this study, two optimal algorithms, exhaustive search and dynamic programming, were embedded into the system as an integrated edging and trimming component to maximize lumber value recovery.

Before edging and/or trimming, the two faces of the flitch are merged together and wane allowances on both edges of the flitch are taken into account. It is assumed that the outermost location of an edging line is in place to make sure that the total length of the wane on either edge equals half of the length of the flitch. This is also the maximum allowable wane for the FAS grade. All other wane left on the flitch is treated as defects and represented with rectangles. If the current flitch satisfies the FAS lumber grade, then the edging and trimming optimization will terminate and return the lumber

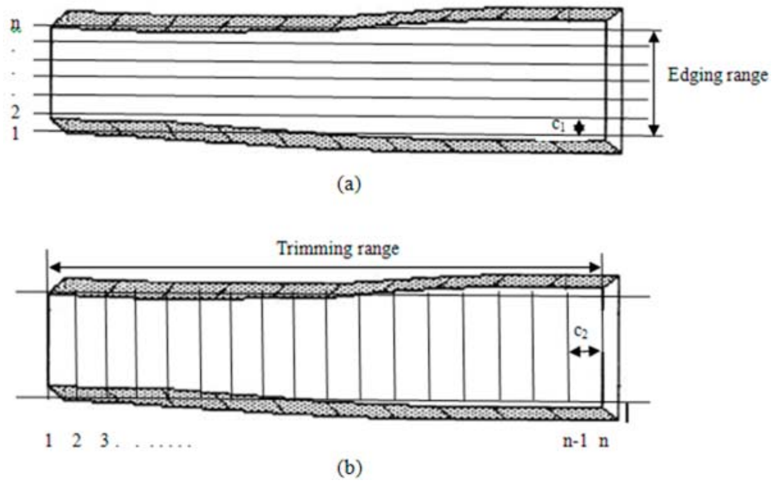


Figure 4.—Potential cutting lines for flitch edging and trimming.

value because no improvement can be achieved by edging and/or trimming operation. Otherwise, the edging and/or trimming algorithms will be recalled to achieve the optimal solution, and multiple pieces of lumber will be generated.

Exhaustive Search Algorithm

This edging and/or trimming algorithm will try all possible combinations of edging and/or trimming lines to find the optimal pattern. For the integrated flitch edging and trimming, if there were n_1 and n_2 edging increments for each edge of flitch, and n_3 and n_4 increments at both ends, there would be a total of $(n_1 \times n_2 \times n_3 \times n_4)$ combinations of cutting lines. Each set of edging and/or trimming lines determines the shape of the edged and/or trimmed flitch. Information on length, width, surface measure, and defects of the edged and/or trimmed flitch is then passed to the lumber grading component for grading. The combination of grade and SM determines the board's value based on the lumber price. The solution that yields the maximum lumber value will be the optimal edging and/or trimming solution.

Dynamic Programming Algorithm

Similar to primary log sawing at each sawing face, the positions of all potential edging and trimming lines are pre-defined by dividing a flitch into equidistant levels in horizontal (Fig. 4a) and vertical (Fig. 4b) directions, respectively. This allows the lumber edging and/or trimming problem to be formulated as a set packing problem to maximize the total lumber value. Given the lumber width, length, sawing kerf width, and edging and trimming resolutions, the recursive mathematical equations for flitch edging or trimming can be written as equation (3) based on Bhandarkar et al. (2008).

$$\begin{cases} v^*(i+1)=\max\limits_{k\in[1,m]}\left(v^*\left(i+1-\left\lceil \frac{W_k}{c_1}\right\rceil-\left\lceil \frac{K}{c_1}\right\rceil\right)+g\left(i+1-\left\lceil \frac{W_k}{c_1}\right\rceil, i+1\right)\right), \text{ for edging only} \\ v^*(i+1)=\max\limits_{l\in[1,n]}\left(v^*\left(i+1-\left\lceil \frac{L_l}{c_2}\right\rceil-\left\lceil \frac{K}{c_2}\right\rceil\right)+g\left(i+1-\left\lceil \frac{L_l}{c_2}\right\rceil, i+1\right)\right), \text{ for trimming only} \end{cases} \qquad (3)$$

To integrate edging and trimming together, let $g(i, j, k, l)$ be the lumber value between edging lines i and j and trimming lines k and l , $v^*(i, j)$ be the optimal value for the horizontal edging lines from 1 to

i and vertical trimming lines from 1 to j. Based on Bhandarkar et al. (2008), the integrated edging and trimming flitch problem can be formulated as equation 4 as follows:

$$v^*(i+1, j+1) = \max_{k\in[1,m]}(\max_{l\in[1,n]}((v^*(i+1-\left\lceil \frac{W_k}{c_1} \right\rceil - \left\lceil \frac{K}{c_1} \right\rceil, j+1-\left\lceil \frac{L_l}{c_2} \right\rceil - \left\lceil \frac{K}{c_2} \right\rceil) +$$
$$g(i+1-\left\lceil \frac{W_k}{c_1} \right\rceil, i+1, j+1-\left\lceil \frac{L_l}{c_2} \right\rceil, j+1)))) \quad (4)$$

where $W_k = \{W_1, W_2, \cdots, W_m\}$ is the allowed set of lumber width, $L_l = \{L_1, L_2, \cdots, L_n\}$ is the allowed set of lumber length, c_1 and c_2 are the edging and trimming intervals, respectively, and K is the sawing kerf. The edging and trimming interval was 0.5 inch and 6 inches, respectively. The minimum lumber width and length can be 3 inches and 4 feet, respectively. Any lumber width and length that equals the multiple of respective edging and trimming interval are allowed.

Cant Resawing and Lumber Grading

Deciding whether to make a cant or to saw the cant into lumber is a common issue for sawmill personnel. If they would like to compare the total lumber value derived from different sawing methods for each log, the value of the central cant must be considered. If cant resawing occurs, the boards generated from the cant will be sent to the edging and trimming optimization component to obtain the optimal lumber value. As in the case of primary log sawing for each face, a similar DP algorithm can be used to resaw the central cant. The final cant will be divided into equidistant potential sawing lines in horizontal or vertical direction, and the final sawing pattern will be the one that yields the highest total lumber value.

The lumber grading component is based on a hardwood lumber grading routine developed by Klinkhachorn et al. (1988). The heuristic algorithm is designed to assign the National Hardwood Lumber Association (NHLA) lumber grade to a piece of lumber (Lin et al. 2010). The basic principle is that the potential lumber grades are tested sequentially, starting from the highest lumber grade and working downward until the satisfied lumber grade is found. After edging and/or trimming, the processed flitch information including dimension, shape, and defect is called by the lumber grading component to determine the lumber grade. Based on lumber prices of different grades, the lumber value can be derived. The lumber prices can be updated whenever necessary. As a module, this grading algorithm can be easily combined with other modules within the system.

SYSTEM APPLICATION

Data Collection

A total of 30 hardwood logs in two species, yellow-poplar (*Liriodendron tulipifera*) and red oak (*Quercus rubra*), were collected at two local small sawmills in central Appalachia. These sawmills were typical mills across the region in terms of equipment and sawing methods. Log information such as log length, small-end and large-end diameters, log diameter at each foot interval, and log sweep were measured. To get log sweep, two stadia rods were put against both ends of the log and a string was horizontally stretched between the rods at the height of the upper end of the log (Fig. 3). We measured the distances between the string and the log surface at each 1-foot interval using a folding ruler. The largest distance and the corresponding log diameter at this position were also measured. The distances from the opposite log surface to the ground at the large and small ends were computed

Table 1.—Characteristics of lumber from the sample logs

Statistic categories	Length (feet)	Width (inch)	Thickness (inch)	SM[a]	Volume (bd ft)	Value ($)
Min	6	4.00	0.94	2	2.75	0.66
Max	14	9.00	2.25	7	13.13	6.43
Mean	8.69	5.94	1.39	4	5.99	2.49
Stdv[b]	1.65	1.04	0.14	1.14	1.7	1.13

[a] Surface measure.
[b] Standard deviation.

Table 2.—Lumber prices based on grades ($/thousand board feet)

Species	Thickness (inch)	Lumber grades FAS	F1F	Select[a]	1COM	2COM	3COM
Red oak	4/4	705	695	598	500	375	300
	5/4	850	840	685	530	420	355
	6/4	905	895	763	630	435	375
	8/4	920	910	805	700	445	385
Yellow-poplar	4/4	600	590	475	360	290	235
	5/4	600	590	488	385	305	250
	6/4	615	605	503	400	310	260
	8/4	615	605	513	420	325	260

[a] Price was the average of price of the F1F and 1COM.

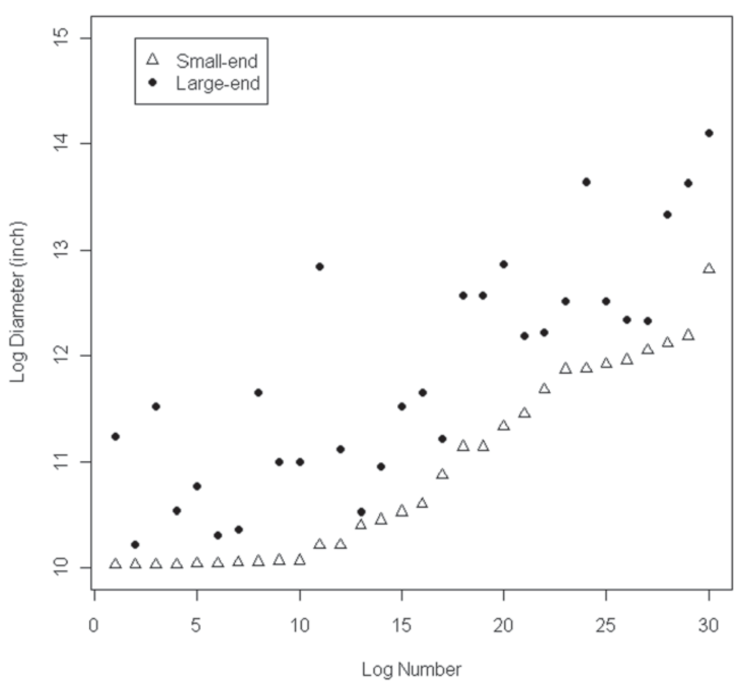


Figure 5.—Log diameter distribution order by small-end diameter.

based on the measurements. External log defects data were also collected including defect type, defect distance from one end of log, and defect size. Based on the collected external defects, internal log defects were predicted using the models developed by the U.S. Forest Service (Thomas 2008). The small-end diameters of the sample logs ranged from 10 to 13 inches with log length from 8 to 14 feet (Fig. 5). Log tapers range from 0.01 to 0.026 inch/foot and log sweep ranged from 0 to 3.25 inches. Lumber length (feet), width and thickness (inches), and volume (board feet) were measured (Table 1). The grade and surface measurement of the lumber were determined by a certified NHLA grader at each sawmill. Lumber prices were based on Hardwood Market Report for Appalachian Hardwoods in April 11, 2009 (Table 2).

RESULTS

Optimal Solution vs. Sawmill Production without Edging and Trimming

Lumber Value and Volume Recovery

Without considering lumber edging and trimming, the lumber width is assumed to be the narrowest clear width along the flitch length. Comparisons between the optimal solution and sawmill production in terms of lumber value/volume are presented in Table 3. The sawmills could improve lumber value by 7.8 percent and 10.3 percent, respectively, by using the heuristic and DP algorithms to aid the sawing process. Suppose that the average board value was priced at $0.50 per board foot and one million board feet went through the log sawing process annually; the potential gain in lumber value could be as high as $39,000 to $51,500 per year. However, we did not consider the

Table 3.—Lumber values and volume by log from actual sawmill, heuristic, and dynamic programming algorithm without edging and trimming optimization

	Lumber value ($)			Lumber volume (board foot)		
Log number	Actual	Heuristic	Dynamic	Actual	Heuristic	Dynamic
1	17.67	20.83	21.03	38	39.15	39.46
2	31.76	35.05	34.24	52.31	51.07	51.4
3	30.77	33.6	34.87	57.13	59.42	59.75
4	40.27	42.52	42.89	64.44	66.12	64.69
5	33.51	35.06	36.48	53.31	55.31	56.5
6	23.07	25.37	26.34	43	44.52	45.43
7	21.33	21.95	23	38.69	38.97	39.29
8	26.28	28.07	28.69	48.63	49.41	50.74
9	28.89	31.94	32.49	51.19	51.92	54.83
10	18.46	19.14	21.76	39.81	38.97	39.29
11	35.61	38.18	39.87	73.75	74.12	73.19
12	23.15	25.67	27.22	59.01	58.96	59.44
13	18.03	19.58	20.7	57.31	57.06	61.3
14	28.22	30.89	30.05	64.69	65.36	66.06
15	20.33	21.36	21.62	52.19	49.8	49.86
16	12.42	13.01	14.02	39.13	42.23	42.09
17	21.9	24.52	25.06	61.75	60.59	59.55
18	36.16	38.12	38.86	69	68.57	71.34
19	13.73	14.74	15.12	40.75	42.18	42.35
20	15.74	17.96	18	39.06	40.66	40.92
21	19.22	20.69	20.83	53.69	54.2	57.05
22	17.12	19.12	19.31	50.73	55.84	55.52
23	15.21	16.42	16.63	47.19	49.42	49.36
24	22.03	23.58	24.24	58.31	57.15	61.3
25	31.22	32.66	32.9	74.69	77.58	77.23
26	25.69	28.39	28.81	40.88	43.23	43.07
27	29.25	31.63	30.72	48.63	48.97	49.17
28	32.77	33.29	35.87	58.13	59.43	59.95
29	31.88	34.79	34.82	46.81	48.97	49.36
30	24.54	26.23	26.54	43.72	46.57	46.74

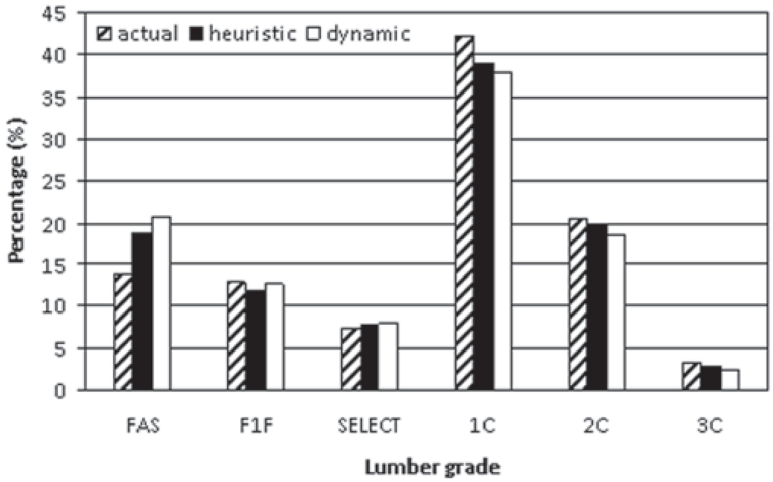


Figure 6.—Lumber grade distribution without exhaustive edging and trimming.

cost of measuring out the defects on every log when calculating lumber value recovery. The lumber volume could be increased by 1.9 percent and 3.2 percent, respectively, using the optimal algorithms. The comparisons indicated that the lumber volume loss in sawmills was partly attributable to value loss. It was noted that high volume recovery tends to result in high lumber value recovery. For example, when using the heuristic and DP algorithms to optimize log sawing, the average lumber volume per log was 53.19 board feet and 53.87 board feet, respectively, and lumber value averaged $26.81 and $27.43 per log, respectively. The average lumber value achieved using the DP algorithm was not always greater than the value generated by the heuristic algorithm because the selected interval in dynamic programming process has an effect on the precision of the DP solution.

Lumber Grade Recovery

We found that the distribution of lumber grades differed among different sawing methods (Fig. 6). Approximately 33.9 percent of lumber produced was graded as Select or higher grades by sawmills, while the number improved to 38.3 percent and 41.4 percent using the heuristic and dynamic programming algorithms, respectively. In sawmills, 42.3 percent, 20.6 percent, and 3.2 percent of lumber were graded as 1COM, 2COM, and 3COM, respectively. If the heuristic algorithm was used to optimize log sawing, 39.0 percent, 19.9 percent, and 2.9 percent of lumber produced were with grades of 1COM, 2COM, and 3COM, respectively. If using dynamic programming, 37.8 percent of lumber were 1COM, 18.4 percent were 2COM, and 2.4 percent were 3COM. Therefore, lumber grades could be improved through optimization, resulting in an increase of the final lumber value recovery.

It was found that log sweep has a significant effect on lumber value and lumber volume recovery compared to straight logs. For example, for two logs 8 feet in length and 10.8 inches in small-end diameter with six defects, the lumber value and volume were $24.54 and 43.72 board feet for the straight log. However, the lumber value and volume could drop to $18.67 and 35 board feet for another log with 2.75 inches of sweep. In addition, lumber from sweepy logs is also prone to warp during drying (Denig et al. 2005). Therefore, a decision must be made before the sawing process to avoid unnecessary sawing costs for severely sweepy logs.

Table 4.—Lumber values from edging-only optimization and trimming-only optimization

		Edging only	Trimming only	Edging and trimming
		($)		
Heuristic log sawing	Exhaustive	834.82	804.99	853.42
	Dynamic programming	817.73	791.09	830.97
Dynamic log sawing	Exhaustive	821.70	810.51	844.70
	Dynamic programming	821.47	806.01	838.08

Edging or Trimming Only Optimization

The lumber values from edging-only and trimming-only optimization using an exhaustive search and the DP algorithm were compared (Table 4). With exhaustive search-based edging-only optimization, an overall average value recovery could be 97.8 percent or 97.3 percent by using the heuristic and DP log sawing algorithms, respectively. However, an overall average lumber value recovery could be 94.3 percent and 95.2 percent using trimming-only optimization. With DP-based edging-only optimization, an overall average value recovery was 98.4 percent or 98.0 percent by using heuristic and DP log sawing algorithms, respectively. An overall average value recovery would be 96.0 percent or 96.2 percent using trimming-only optimization. The findings suggest that edging optimization has a greater impact on lumber value than trimming optimization for waney edged boards. In the system, the board length generated from the log sawing was assumed as the same as log length, so there was little wane generated at both ends of the boards.

Optimal Solution vs. Sawmill Productions with Edging and Trimming

Lumber Value Recovery

In this case, the flitch produced from primary log sawing was edged and trimmed through either exhaustive or dynamic programming optimization. We compared the actual lumber value by sawmills and the simulated solutions (Table 5) and found that the lumber value generated from log sawing using heuristic or DP algorithms could increase 11.9 percent and 14.3 percent using exhaustive search for flitch edging and trimming, respectively, while the lumber value could improve 10.9 percent and 12.8 percent using DP for flitch edging and trimming. The results indicated that more lumber value recovery can be achieved when exhaustive search is used to optimize flitch edging and trimming. However, it should be noted that the exhaustive search typically needs more computer processing time than dynamic programming.

Lumber Grade Recovery

The distribution of lumber grades produced by using the optimal algorithms and actual lumber production with consideration of edging and trimming is shown in Figures 7a and 7b. It was found that the distribution of lumber grades was similar between the exhaustive and DP algorithms for edging and trimming operations. However, the lumber grade distribution among different log sawing methods (sawmills, heuristic, and dynamic programming) was different. For example, when using the exhaustive search algorithm to optimize flitch edging and trimming, 33.9 percent, 40.2 percent, and 43.2 percent of lumber produced were Select or higher grades at swmills, using heuristic, and dynamic programming algorithms, respectively. In the actual log sawing production, 42.3 percent, 20.6 percent, and 3.2 percent of lumber were with grades of 1COM, 2COM, and 3COM,

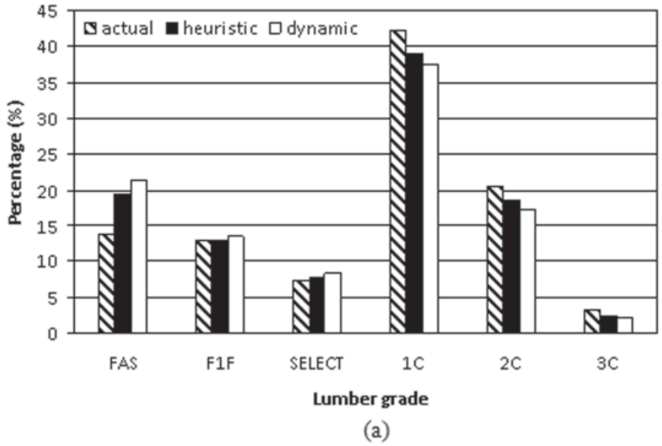
Table 5.—Lumber values by log from actual sawmill, heuristic and dynamic programming algorithm with exhaustive search and dynamic programming for edging and trimming optimization

		Exhaustive edging and trimming		Dynamic edging and trimming	
Log number	Actual	Heuristic	Dynamic	Heuristic	Dynamic
1	17.67	20.5	21.53	20.5	21.47
2	31.76	35.72	34.74	35.66	34.46
3	30.77	34.24	35.37	34.23	35.03
4	40.27	45.08	47.39	46.17	46.97
5	33.51	35.85	36.98	35.68	36.48
6	23.07	25.44	26.84	26.75	26.55
7	21.33	24.46	26.18	22.53	24.33
8	26.28	30.64	29.19	30.66	30.46
9	28.89	33.08	33.19	33.19	32.99
10	18.46	19.72	22.26	19.66	21.46
11	35.61	38.83	41.29	38.79	39.59
12	23.15	26.23	27.72	26.26	26.56
13	18.03	21.84	22.2	20.14	20.94
14	28.22	31.71	31.81	31.49	31.29
15	20.33	21.82	23.12	21.93	22.73
16	12.42	13.59	15.52	13.56	14.36
17	21.9	23.7	25.56	23.1	25.4
18	36.16	39.81	39.36	38.73	39.07
19	13.73	15.4	16.62	15.29	16.09
20	15.74	18.67	19.25	18.52	18.72
21	19.22	23.49	21.67	23.27	23.07
22	17.12	19.77	19.81	19.69	19.59
23	15.21	18.98	17.13	16.98	17.08
24	22.03	25.84	25.83	24.16	24.96
25	31.22	33.25	33.4	33.26	33.16
26	25.69	28.94	29.31	28.98	30.08
27	29.25	32.46	31.22	32.24	32.04
28	32.77	33.85	36.37	33.91	34.71
29	31.88	35.49	35.32	35.41	35.21
30	24.54	26.78	27.03	26.72	26.92

respectively. If the heuristic algorithm was used to optimize log sawing, 39.1 percent, 18.5 percent, and 2.3 percent of lumber were graded as 1COM, 2COM, and 3COM, respectively. When using the dynamic programming algorithm to optimize log sawing, 37.5 percent, 17.2 percent, and 2.1 percent of lumber produced were with grades of 1COM, 2COM, and 3COM, respectively.

Optimal Log Sawing with or without Optimal Edging and Trimming

Greater lumber value recovery could be achieved when log sawing was integrated with flitch edging and trimming optimization. At least 3.1 percent more value could be recovered when integrating log sawing optimization with flitch edging and trimming, and the maximum value improvement could be as high as 4.1 percent. This is reasonable because severe edging can result in a failure to consider



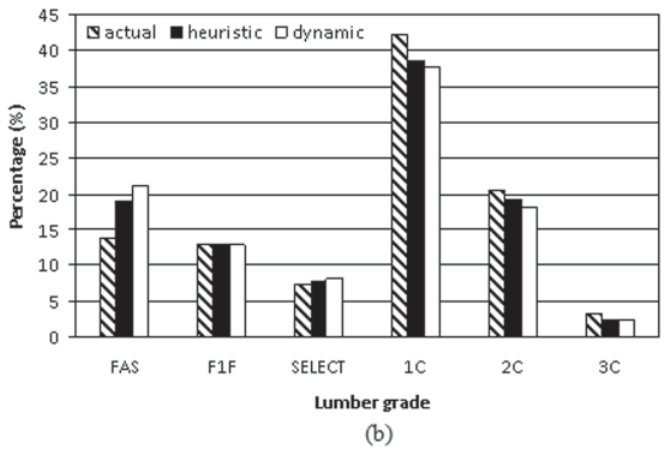


Figure 7.—Lumber grade distribution with optimal edging and trimming operations. (a) Lumber grade distribution with exhaustive edging and trimming; (b) lumber grade distribution with dynamic programming edging and trimming.

the numerous possible combinations of grades and surface measures from each board. Severe edging removes all wane from a board, but it may exceed the minimum requirements specified in the NHLA grading rules. Even though the board grade could be upgraded in some cases, the reduction of surface measure due to severe-edging could result in a total lumber value loss. Therefore, when edging and trimming optimization are ignored, the final log sawing solution is suboptimal.

CONCLUSIONS AND DISCUSSION

This 3D visual log optimization system that integrated primary and secondary log breakdown simultaneously for lumber production could be used as a decision aid for lumber production planning as well as a tool to train novice sawyers. A prototype implementation of the system showed significant lumber value recovery gains could be achieved. Without edging and trimming optimization, sawmills could improve lumber value by 7.8 percent and 10.3 percent, respectively, if heuristic and dynamic programming algorithms were used for log sawing optimization. With edging and trimming optimization, however, the lumber value recovery could be up to 11.9 to 14.3 percent using exhaustive search for flitch edging and trimming, or 10.9 to 12.8 percent using dynamic programming for flitch edging and trimming. The results indicated that better solutions could be achieved by integrating primary and secondary log breakdown in the system. Other factors also attributed to the difference of lumber value recovery between sawmills and using optimization algorithms. In a real sawmill, these factors could be operator experience, operation errors, and mill equipment. All these factors need to be considered in the computer simulation system.

The system can be used together with a cost effective and affordable 3D log laser scanning system to enhance the production efficiency and speed up the production process. The U.S. Forest Service, in cooperation with Concord University and Virginia Tech, has developed a full shape 3D log scanner to detect severe log surface defects using relatively low-cost equipment ($30,000 plus integration labor cost) (Thomas 2006). Without the need of flitch scanning, the integrated log sawing and flitch edging and trimming system can predict internal defects on the flitch and save extra scanning time and cost. In addition, sawing errors may occur when sawing a log without considering flitch edging and trimming simultaneously. Errors in edging and trimming stage including cutting and/ or positioning the flitches causes different flitches to be edged and trimmed. The original (integrated) edging and trimming decisions are not used to these flitches, which should be applied to improve lumber value recovery, so a suboptimal solution will generate accordingly.

A cautionary note: the log sawing method that combined primary breakdown and secondary breakdown presented here assumes that logs are positioned and an opening face was determined before sawing. Of course, the sawyer can choose an alternative angular (such as from 0 to 360 degrees) and opening face width (such as from 3 to 6 inches) placements. In addition, the current method can be nested within that two loops (angular and opening face width) and evaluated at each placement to find the best sawing results. However, increased levels of loop will increase the computational burden and need enough memory to save millions of variables.

The optimization precision could be improved by reducing the stage interval of sawing, edging and trimming optimization at the expense of computing time. When considering sawing, edging and trimming optimization simultaneously, the log breakdown problem becomes a 3D log sawing problem, which requires more computer execution time to generate an optimal sawing pattern. A smaller interval provides more opportunities to discover better solutions, but the optimization process can take longer, especially for poorly shaped large logs with more defects. The solutions from the heuristic algorithm were better than those from the dynamic programming algorithm in some cases due to a relatively larger sawing stage interval. The edging and trimming intervals chosen also had an effect on lumber value recovery. It should be noted that time is important for sawmills. To increase the profitability of the sawing business, the processing decisions at each stage must be delivered in a timely manner. Therefore, appropriate intervals should be determined to optimize log breakdown patterns as well as keep sawmills production running.

We should also note three limitations associated with this system, which should be taken into account in future studies: (1) considering external log defects, internal defects, and log shapes simultaneously to determine opening face, (2) improving 3D log model by using polygonal data obtained by laser scanning instead of circular representation of log cross sections, and (3) employing more sawing, edging, and trimming stage intervals to increase the flexibility of the system.

ACKNOWLEDGMENTS

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PREDICTING INTERNAL RED OAK (*QUERCUS RUBRA*) LOG DEFECT FEATURES USING SURFACE DEFECT MEASUREMENTS

R. Edward Thomas[1]

Abstract.—Determining the defects located within a log is crucial to understanding the tree/log resource for efficient processing. However, existing means of doing this non-destructively requires the use of expensive x-ray/CT (computerized tomography), MRI (magnetic resonance imaging), or microwave technology. These methods do not lend themselves to fast, efficient, and cost-effective analysis of logs and tree stems in the mill. This study quantified the relationship between external defect indicators and internal defect characteristics for red oak logs. A series of models was developed to predict internal features using visible external features: surface indicator width, length, rise, and log diameter. Good correlations and small prediction errors were observed with sound (sawn), overgrown, and unsound knot defects. For less severe defects such as adventitious buds/clusters and distortion-type defects, weaker correlations were observed, but the magnitude of prediction errors was small and acceptable.

INTRODUCTION

One of the major emphasis areas today in hardwood research is the development of equipment and a methodology to accurately sense internal defect location and structure. Determining the location and characteristics of defects located inside logs promises to dramatically improve log recovery in terms of both quantity and quality (Steele et al. 1994). In addition, accurate internal defect information would permit researchers to analyze, refine, and expand log grading rules, multi-product potential, stand differences, and impact of silvicultural treatments on quality in ways previously not available or economically feasible. The goal of this research is to provide a mathematical method of predicting internal defect size and location based on external surface indicators. This study was limited to the most common defect types that have the greatest impact on hardwood quality (tree or lumber grade).

Although there are many benefits to determining internal log information, an inexpensive and efficient method of obtaining these data does not exist today. Researchers are currently examining various approaches to this problem including the use of x-ray/CT (computerized tomography), ultrasound, MRI (magnetic resonance imaging), or radar technology (Chang 1992). Some high-volume softwood lumber mills in Europe and the Pacific Northwest have installed three-head x-ray scanners. This type of scanner uses three or four x-ray transmitters and detectors to capture internal log defect data. Although these types of scanners operate much faster than CT scanners, they obtain lower quality/resolution data. Although x-ray/CT and MRI methods show promise, the technology is prohibitively expensive and does not permit fast, efficient analysis of logs and tree stems. Both CT and three-head x-ray systems are still being used only on smaller diameter logs due to energy level issues.

Researchers have studied the relationships among surface indicators and internal defect manifestation in depth for various hardwood and softwood species. Schultz (1961), in examining German beech (*Fagus sylvatica*), found that the ratio of the bark distortion width to bark distortion length in this species is the same as the ratio of the stem when the branch was completely healed over to the current

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stem diameter. However, for species with heavier irregular bark, such as hard maple, he found that it was difficult to judge the clear area above the defect in this manner.

Hyvärinen (1976) explored the relationships among the internal features of grain orientation and height of clear wood above an encapsulated knot defect and the external features of surface rise, width, and length for sugar maple (*Acer saccharum*). The sugar maple defect data were collected from 44 trees obtained from three sites in upper Michigan. Hyvärinen used simple linear regression methods to find good correlations among clear wood above defects, bark distortion width, length, and rise measurements, as well as age, tree diameter, and stem taper. The best simple correlation was with diameter inside bark (DIB) ($r = 0.66$) and a 0.66-inch standard error of estimate. Correlation was further improved by using a stepwise regression method. The final model ($r = 0.74$) used bark distortion vertical size and DIB as the most significant predictor variables for predicting encapsulation depth.

A similar study was conducted on a sample of 21 black spruce (*Picea mariana*) trees collected from a natural stand 75 km north of Quebec City (Lemieux et al. 2001). Three trees, each with three logs, were selected from which a total of 249 knot defects were dissected and their data recorded. The researchers found better correlations between external indicator and internal characteristics in the middle and bottom logs as compared to the upper logs. Strong correlations ($r > .89$) were found among the length and width of internal defect zones and external features such as branch stub diameter and length. The defects were modeled as having three distinct zones corresponding to the manner in which the penetration angle changes over time in black spruce. The penetration angle is the angle at which a line through the center of the defect intersects the log surface.

Carpenter's (1950) examination of surface indicators found that although the frequency and occurrence of surface indicators within a given species vary by region, in general the same indicator will be found with its defect in the underlying wood. Thus, although certain defect types may be more prevalent in some regions, the underlying manifestation of the defect would remain more or less consistent across regions. Further, growth rate will vary from region to region (or site to site within the same region), so the defect encapsulation rate will differ also. However, the rate at which the encapsulation occurs and the degree to which the defect is occluded or covered over by clear wood are indicated in the bark pattern. Shigo and Larson (1969) discovered that the ratio of defect height to width is a strong indicator of defect depth with respect to the radius of the stem at the defect (Fig. 1). The faster the diameter growth, the faster the defect is encapsulated and the faster the bark distortion pattern changes.

More recently, the relationships among external defect indicators and internal features were examined for yellow-poplar *(Tulipifera liriodendron*) (Thomas 2008). This study found statistically significant correlations between external indicators and internal features. The strongest correlations occurred with the most severe defect types, i.e., overgrown knots, overgrown knot clusters, sound knots, and unsound knots. These defects are the most recent and therefore the least occluded. In almost all cases, the correlations observed with the severe defect types were significant ($\alpha < 0.01$). Conversely, the weakest correlations involved the least severe and most occluded defect types, i.e., adventitious knots, adventitious knot clusters, light distortions, and medium distortions. In several cases, the correlations between external and internal features failed to be statistically significant ($\alpha < 0.01$) for the less severe defect types.

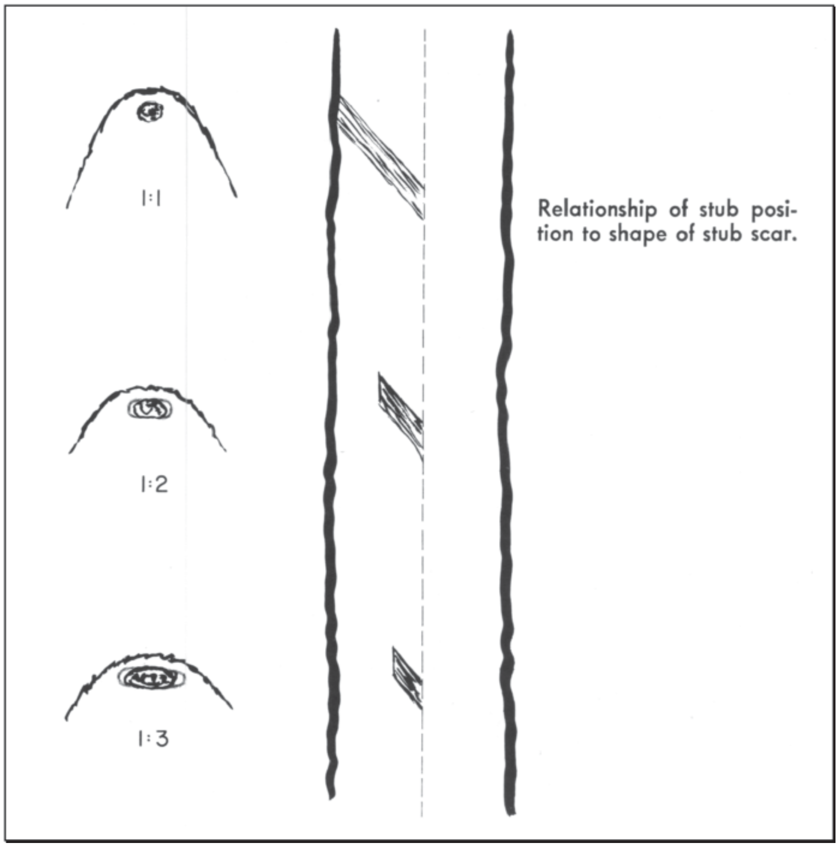

Figure 1.—Encapsulation depth and stub scar relationship ratio (Shigo and Larson 1969).

METHODS

Sample Collection

Red oak (*Quercus rubra*) defect samples were collected from two sites in West Virginia: West Virginia University Forest (WVUF) near Morgantown (elevation: 2,300 feet) and the Mead Westvaco Forest (MWF) near Rupert (elevation: 3,200 feet). The two sites are separated by about 125 miles. From each site, 33 trees were randomly selected. For each tree the number of defects by type was counted. The counts were used to develop a random sampling plan. The goal was to collect four defects of each type from each tree, whenever possible. For example, if there were eight sound knots on the tree, every second sound knot was selected. Of course, not all trees have four defects of every type. In other cases, selecting one defect would prevent another from being selected due to defect overlap. In these cases, preference went to the least common defect type on that tree and a different occurrence of the second defect type was used. The number of defect samples obtained from each site by defect type is shown in Table 1. In most cases, approximately equal numbers of each type of defect were obtained from each site.

Sample Processing

All defects were identified according to the characteristics as defined in Defects in Hardwood Timber (Carpenter et al. 1989). Once a defect was located and classified, the section containing the defect was cut from the log. The defect sections ranged from 12 to 24 inches in length. If, upon dissection, the inner portion of the defect was not completely contained within the section, the sample was

Table 1.—Types and numbers of defects collected by site and overall

Defect type	Location: WVU Forest	Location: Mead Westvaco Forest	Total
Adventitious Knot (AK)	54	51	105
Adventitious Knot Cluster (AKC)	27	47	74
Heavy Distortion (HD)	52	46	98
Light Distortion (LD)	2	37	39
Medium Distortion (MD)	70	63	133
Overgrown Knot (OK)	45	114	159
Overgrown Knot Cluster (OKC)	0	48	48
Sound Knot (SK)	19	36	55
Sound Knot Cluster (SKC)	1	13	14
Unsound Knot (UK)	30	31	61
Unsound Knot Cluster (UKC)	0	13	13
Wound (WND)	0	43	43
Total	300	542	842

discarded. For each sample the following information was recorded: defect type, surface width (across grain) and length (along grain), growth rate (rings per inch), and bark thickness. The sample was then sawn into 1-inch-thick slices. This resulted in a photo series showing the defect penetrating the log (Fig. 2). For each slice, the depth, defect width, length, and distance of defect center to notch bottom center were recorded. When a defect terminated between slices, it was assumed that it terminated at the halfway point through the slice.

Modeling Statistics

A series of chi-squared tests was used to test for outliers in the internal/external dataset (Komsta 2006) Data identified by the tests as outliers were examined and corrected if in error by remeasuring the sample. The data were grouped by defect type. With the R statistical analysis program, stepwise muliple-linear regression analyses were used to test for correlations among surface indicators and internal features (R Development Core Team 2006). The independent variables used were surface indicator width (SWID), length (SLEN), rise (SRISE), and log diameter inside bark (DIB). These variables were selected because they are measurable during log surface inspection. Area (SWID * SLEN), $SLEN^2$, and $SWID^2$ also were examined as potential predictor variables. The dependent variables selected were (1) rake (penetration angle), (2) clear wood above defect, (3) total depth, (4) halfway-point cross-section width (HWID), and (5) halfway-point cross-section length (HLEN). These variables permit an internal model of a defect to be constructed and determine an approximate internal location (Fig. 3).

Within each defect type class, the data was randomly partitioned into two groups using the caTools package (Tuszynski 2006) for R. The first group contains approximately 66.7 percent of the records and was used for model development and determining the internal/external feature correlation statistic. The second set contained the remaining records and was used for testing the prediction models (model validation set). Table 2 shows the numbers of observations used in the model development and testing steps.

Figure 2.—Series of internal defect sections for a heavy distortion defect surface indicator.

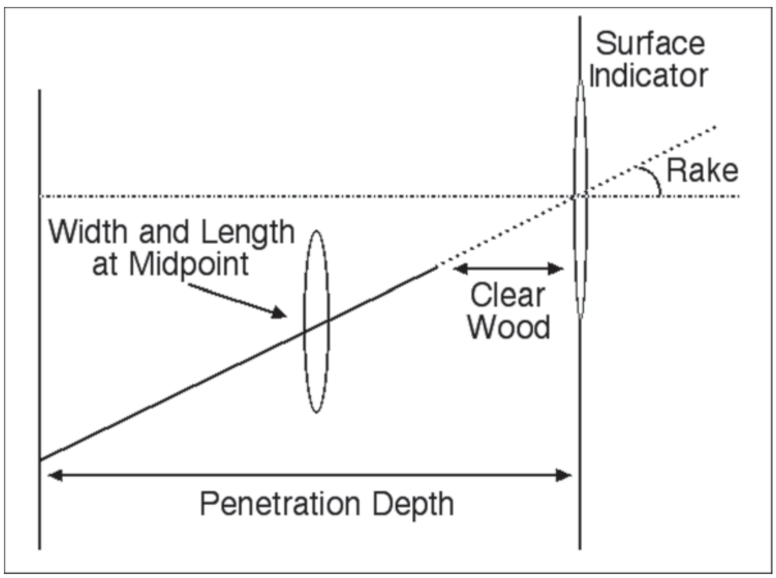

Figure 3.—Illustration of internal features predicted by the model.

Table 2.—Numbers of observations used in model development and testing by defect type

Defect	Number of observations		Total
type	Model dataset	Testing dataset	observations
AK	70	35	105
AKC	49	25	74
HD	65	33	98
LD	26	13	39
MD	88	45	133
OK	105	54	159
SK	37	18	55
UK	40	21	61
OK/SK/UK	182	93	275
OKC/SKC/UKC	46	25	71
Total	708	362	1,070

RESULTS

Correlation results for model development and significant predictor variables are presented in Table 3. A significance level of 1 percent was used for all tests. Table 3 has two major sections: model development and model testing. In each section, the correlation coefficient, significance, and the mean-absolute error (MAE) of the correlation are reported. MAE is the mean of the absolute value of the residual errors for the fitted equation. MAE indicates the +/- error range that can be expected using the fitted equation to predict defect features.

Knot Defects

Model development with the severe knots, OK, SK, and UK, discovered strong significant correlations ($\alpha < 0.01$) in almost all instances (Table 3). The exception was with overgrown knots and predicting clear area (Clear) above the encapsulated defect. Clear area above an encapsulated knot defect occurred in only a few samples, so it was weakly correlated with external features. The strength of the relationship (multiple adjusted R^2) among interior halfway point cross-section width (HWID) measurement and external features ranged from 0.53 to 0.74. Similar results were found among external features and the halfway point cross-section length (HLEN) measurement with adjusted multiple R^2 values ranging from 0.40 to 0.87. The correlation of total defect penetration depth (DEPTH) to external features ranged between 0.40 and 0.63, which was not as strong as the correlations observed with yellow-poplar, which ranged from 0.63 to 0.73 (Thomas 2008). In many cases, the defects in the samples terminated before reaching the pith, indicating an adventitious knot. This decreased the significance of DIB as a predictor variable for depth. The correlations (adjusted multiple R^2) among external features and penetration angle (RAKE) ranged from 0.39 to 0.54.

Table 3 lists the most significant independent or predictor variables for each defect type and internal feature. The independent variables are listed in the order of most to least significant. The number of instances where correlations with DIB, SLEN, and SWID were significant was nearly identical at 11, 11, and 12 instances, respectively. Interaction terms had the strongest correlation with internal features in 9 instances while non-interaction terms were the most significant in 12 instances. Correlations involving SWID and SLEN were the most common interaction terms, having a statistically significant correlation six times each. Similarly, SWID and SLEN were the most significant single independent variables, statistically significant five and four times each, respectively. Thus, with the severe knots and knot clusters, most of the strongest correlations to internal features are with the surface width and length of the defect.

The associated MAEs with the model development samples were small in most cases. The MAE values in Table 3 are reported in inches for all measurements except rake angle, which is in degrees. In 10 out of 16 cases for the knot defects, the MAE is 0.75 inch or less. In five instances, the MAE is less than 0.50 inch. In the remaining six cases, four are less than 1 inch and two are 1.15 and 1.05 inches. The MAE values for rake angles ranged between 9 and 12 degrees.

The model testing samples were used to analyze the models' predictive capabilities. The regression equations generated with the model development samples were used to predict internal feature measurements. The correlation coefficient r, the mean absolute error (MAE), and the significance level of the correlation were determined for each defect type and feature combination (Table 3). In

Table 3.—Model development and testing correlation results

		Model Development Results				Model Testing Results		
Defect type	Dependent variable	Multiple adjusted R^2	Mean absolute error	Correlation significant	Significant independent variables	Correlation coefficient 'R'	Mean absolute error	Correlation significant
AK	Hwid	0.15	0.27	Yes	slen	0.52	0.26	Yes
	Hlen	0.26	0.28	Yes	swid, slen, swid*slen, srise*slen	0.32	0.41	No
	Rake	0.12	5.04	Yes	slen, srise, srise*swid	0.51	0.83	Yes
	Depth	0.24	1.45	Yes	dib, swid, slen, srise	0.35	1.57	No
	Clear	0.10	1.27	No	srise, dib	0.40	0.93	No
AKC	Hwid	0.11	0.56	No	swid, srise	0.61	0.82	Yes
	Hlen	0.36	0.43	Yes	slen, swid*srise, slen*srise	0.33	0.81	No
	Rake	0.20	7.15	Yes	swid*srise, srise*dib	0.12	0.95	No
	Depth	0.26	1.35	Yes	dib	0.80	0.90	Yes
	Clear	0.06	1.12	No	srise	0.37	1.04	No
HD	Hwid	0.55	0.20	Yes	dib, swid, slen, dib*swid	0.43	0.28	Yes
	Hlen	0.47	0.43	Yes	slen, dib, dib*swid	0.47	0.44	Yes
	Rake	0.40	9.29	Yes	dib, slen	0.68	8.54	Yes
	Depth	0.27	0.86	Yes	dib, swid	0.51	0.72	Yes
	Clear	0.08	0.67	No	swid, slen, swid*slen	0.31	0.62	No
LD	Hwid	0.19	0.27	No	dib, slen	0.46	0.41	No
	Hlen	0.34	0.65	Yes	slen, srise	0.25	1.09	No
	Rake	0.03	10.06	No	dib, dib*swid	0.14	14.71	No
	Depth	0.09	1.05	No	dib, swid, srise	0.39	1.18	No
	Clear	0.08	0.94	No	slen	0.01	1.00	No
MD	Hwid	0.13	0.24	Yes	swid, slen, swid*slen	0.56	0.29	Yes
	Hlen	0.23	0.34	Yes	swid,dib, swid*slen, dib*slen	0.61	1.78	Yes
	Rake	0.10	10.50	Yes	dib, swid	0.46	9.92	Yes
	Depth	0.16	0.80	Yes	dib, swid	0.63	0.75	Yes
	Clear	0.10	0.86	Yes	dib, swid	0.17	1.09	Yes
OK	Hwid	0.53	0.29	Yes	dib, slen, swid*srise, slen*srise	0.46	0.40	Yes
	Hlen	0.40	0.67	Yes	slen, srise*swid, slen*srise	0.44	0.81	Yes
	Rake	0.42	10.23	Yes	dib, slen, srise, dib*srise	0.60	11.82	Yes
	Depth	0.45	0.96	Yes	dib, dib*swid	0.62	0.88	Yes
	Clear	0.03	0.04	No	swid, srise, swid*srise*slen	0.17	0.04	No
SK	Hwid	0.65	0.38	Yes	swid*slen, swid*dib	0.50	0.75	No
	Hlen	0.66	0.55	Yes	swid, srise, srise*slen, swid*srise*slen	0.61	0.71	
	Rake	0.45	9.18	Yes	dib, swid, swid*slen	0.07	19.59	No
	Depth	0.58	0.98	Yes	slen, swid, swid*dib, slen*dib	0.52	1.45	No
	Clear	--	--	No	--	--	--	No
UK	Hwid	0.74	0.30	Yes	slen, slen*swid, slen*srise, slen*dib, slen*swid*srise	0.08	0.77	No
	Hlen	0.87	0.74	Yes	swid, slen, swid*srise, swid*slen*srise	0.37	1.85	No
	Rake	0.54	10.29	Yes	swid, swid*dib	0.55	12.22	Yes
	Depth	0.63	0.72	Yes	dib, swid, slen, swid*slen, dib*slen	0.45	1.13	No
	Clear	--	--	No	--	--	--	No

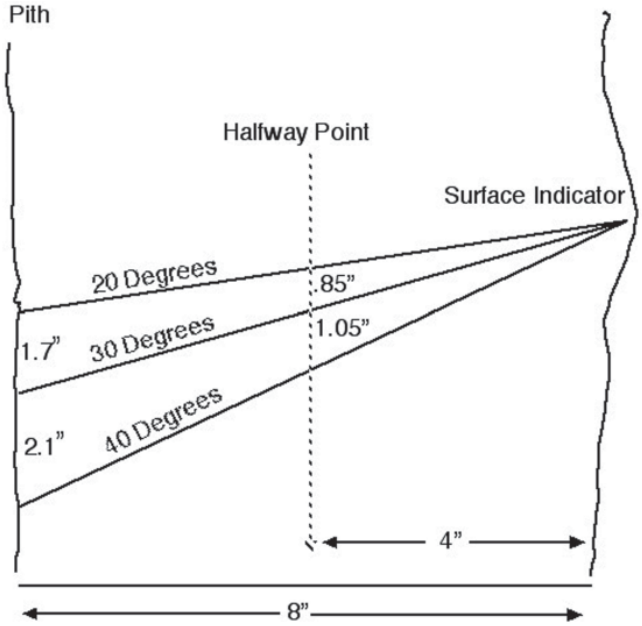

Figure 4.—Impact of rake error on internal defect position.

13 out of 21 instances, the correlation coefficients R were significant ($\alpha < 0.01$). In six instances, the correlation was not significant with the sound and unsound knots. Here the problem was due to sample size, with only 18 and 21 model testing samples for sound and unsound knots, respectively. Similarly, the low numbers of clustered knots, OKC, SKC, and UKC, prevented any analyses by individual type, and these data were not examined.

Overall, the highest correlation coefficients (R) occurred with overgrown knot samples. For all severe knot defects, HWID had the smallest MAE, ranging from 0.29 to 0.41 inch. The MAE for the predicted HLEN values also was acceptable and ranged from 0.71 to 0.81 inch where the correlation was significant. The MAE with predicted depth was lowest with overgrown knots with a value of 0.88 inch. Except for sound knots, where the correlation was not significant, the MAE for RAKE was similar with values of 11.82 to 12.22 degrees. For a 16-inch diameter log with a defect terminating near the center, a 10-degree error would change the defect center position by 1.7 (10 degrees under estimate) to 2.1 inches (10 degrees over estimate) at the pith, depending on degree (Fig. 4). The difference in defect position at the halfway point would have a maximum positional variance of 0.85 (10 degrees underestimate) to 1.05 inches (10 degrees overestimate) depending on degree.

Bark Distortion Defects

In general, the correlations between external indicator measurements and internal features for bark distortion defects (LD, MD, and HD) were not as strong as those measured for the knot defects. Distortion defects are smaller and have been encapsulated longer than the more recent knot defects. Thus, less surface information is available for these defect types. The model development correlation results for bark distortions are given in Table 3.

The strongest correlations between external and internal features for the minor defects were with the heavy distortion (HD) defect type. In most cases, a heavy distortion is an overgrown knot that has been encapsulated or overgrown to the point where it no longer has any associated surface rise. Thus, it is the youngest of the distortion defects and has the most surface detail present. The correlation (multiple adjusted R^2) of surface features to HWID was comparable to overgrown knots (HD $R^2 = 0.55$ versus OK $R^2 = 0.53$, $\alpha < 0.01$). Similarly, the correlation with HLEN, $R^2 = 0.47$, was also significant and similar to that of overgrown knots, $R^2 = 0.40$. The MAE values for the HWID, HLEN also were acceptable at 0.20 and 0.43 inch. The other correlations for the other HD internal defect features also were significant and similar to that of the overgrown knots, with the exception of encapsulation depth (CLEAR). The MAE for penetration depth (DEPTH) was 0.86 inch and the MAE for RAKE was 9.29 degrees.

The correlations among external and internal features for the medium distortion defects were statistically significant ($\alpha < 0.01$). Although significant, the correlations were not strong. Adjusted multiple R^2 values for the internal features ranged from 0.10 to 0.23. Thus, only a fraction of the variability of the internal features can be explained by this approach. With the light distortion defects, the correlations became weaker and only the correlation with HLEN was significant with a multiple adjusted R^2 value of 0.34.

Analyzing the predictor equations for the model testing samples showed that the models developed for the HD and MD perform well. For these defects only the CLEAR correlation for heavy distortions failed to be statistically significant ($\alpha < 0.01$). The relationship (correlation coefficient R) for halfway-in-width for the HD and MD defects was 0.43 and 0.46 with MAE values of 0.28 and 0.29 inch, respectively. Although the correlations for HD and MD were stronger for HLEN, R=0.44 and R=0.61, respectively when compared to HWID, the MAE increased to 0.44 and 1.78 inches. Note that the model prediction results are nearly the same as the model development results for the MD model development results (Table 3), indicating the adequacy of the models for predicting internal feature size and location.

For the light distortions, none of the prediction models had a significant correlation to the internal features. This is likely due to the small number, 39 total, of light distortion defects. To try to improve the model's predictive ability for LD defects, the HD, MD, and LD data were grouped together and analyzed. This resulted in a larger sample of distortion defects, 177 samples for model development and 91 samples for model testing. However, the correlations between external indicators and internal features were much weaker with higher MAE values than the HD, MD, and LD models individually. From this test, it can be deduced that the classification of distortion defects has a significant impact on the application of the prediction models.

SLEN was the most common, most significant independent variable with 7 occurrences in the prediction models. SWID and DIB were the next most significant terms in 4 and 3 instances, respectively. However, DIB and SWID were the most common overall, occurring in 11 and 9 instances, respectively compared to the 8 instances with SLEN. In addition, the DIB*SWID interaction term was the most significant variable in one instance and a significant variable three other times.

Adventitious Knot Defects

Multiple adjusted R^2 for AK defects ranged from 0.12 to 0.26 for the correlations that were statistically significant ($\alpha < 0.01$). In addition, the MAE values for the HWID and HLEN internal features were 0.14 and 0.15 inch. However, for AK defects, the correlation between the clear area above the defect and external indicators was not statistically significant ($\alpha < 0.01$). Multiple adjusted R^2 for the significant correlations with AKC defect features ranged from 0.20, for the rake angle, to 0.26 and 0.36 for the DEPTH and HLEN features. CLEAR was not significantly correlated to any external feature measurement.

The development dataset correlations for AK and AKC defects were not exceptionally strong. However, except for encapsulation depth, the MAE was small and acceptable. The MAE for penetration angle ranged from 5.04 to 7.15 degrees. In addition, the MAE for HLEN and HWID cross-section measurements ranged from 0.27 to 0.43 inch, where significant. DEPTH, however, had a large MAE range, 1.35 to 1.45 inches. Analyzing the predictor equations using the model testing samples showed that the correlations failed to be statistically significant ($\alpha < 0.01$) for the majority of AK and AKC internal features. For AK defects, only HWID and RAKE had significant correlation coefficients, 0.52 and 0.51, respectively, with surface features. With the AKC defects, HWID and DEPTH were the only internal features that had a significant correlation with the correlation model (correlation coefficient R=0.61 and R=0.80, respectively).

DISCUSSION

Overall, the strongest correlations, both model development and testing, occurred with the most severe defect types (OK, SK, and UK). These defects occurred most recently on the tree and have had the least time to be encapsulated or grown over. Thus, more detail about the surface indicator exists. Conversely, some of the weakest correlations that were discovered involved the least severe defect types (AK, AKC, LD, MD, HD). The adventitious knots/buds and the light and medium distortions were the oldest defects examined and had the longest time to encapsulate. Thus, less surface indicator existed for these defect types. A heavy distortion defect is at the point in the encapsulation process where an overgrown knot has made the transition to a distortion defect. More surface indicator detail exists for this type of distortion than the others, as evident in the predictive power of the HD feature models when compared to the MD and LD defect models. These results closely agree with those from the yellow-poplar defect study (Thomas 2008).

The results from this study indicate that most internal defects can be accurately estimated using external feature data. To date, yellow-poplar and red oak have been studied, resulting in the development of internal defect prediction models. These models will be further developed and tested using samples from additional sites. Models for additional hardwood species are in progress.

The goal of this research was to develop models capable of predicting internal defect features based on external defect characteristics. These models were developed to complement scanning and defect detection research that locates severe defects on hardwood stems (Thomas and Thomas 2011). Recent efforts at West Virginia University (WVU) have created a computer program (Lin et al. 2011) that generates sawing solutions that optimize recovery according to National Hardwood Lumber Association (NHLA) lumber grades, which use the external defect scan data and the predicted internal defect data from this model. As such, the prediction models allow the optimizer to know how deeply encapsulated a given defect is, how big it is, and how deep the defect penetrates the log. For example, the defect models allow the optimizer to know if a defect would be removed when a slab is sawn from the log. All of these research efforts are being pursued as an aid to hardwood sawing.

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RAYSAW: A LOG SAWING SIMULATOR FOR 3D LASER-SCANNED HARDWOOD LOGS

R. Edward Thomas[1]

Abstract.—Laser scanning of hardwood logs provides detailed high-resolution imagery of log surfaces. Characteristics such as sweep, taper, and crook, as well as most surface defects, are visible to the eye in the scan data. In addition, models have been developed that predict interior knot size and position based on external defect information. Computerized processing of complete log shape data, combined with predicted internal defect information, promises to reduce waste and improve grade recovery in primary breakdown operations. RAYSAW is a hardwood log sawing research tool that processes high-resolution 3D laser-scan data and uses internal defect prediction models to estimate the occurrence of defects on sawn board faces. RAYSAW uses mathematically based ray-tracing image generation methods to generate virtual boards that can be graded, remanufactured, or processed into dimension parts using available free software. The RAYSAW sawing simulator allows researchers to examine the impacts of various sawing practices and log quality and shape characteristics on grade and value recovery.

INTRODUCTION

Ray-tracing is a mathematically based methodology for creating photo-realistic images on a computer. As such, ray-tracing creates a 2D picture of a 3D world where objects are defined with light sources and view point (Watkins and Sharp 1992). In ray-tracing, a "light" ray is cast from the observer into the scene onto the objects in the scene. Wherever the light ray intersects an object, a pixel records the color parameters of the intersection point. In addition, the light ray can bounce from object to object, generating photo-realistic object reflections and transparencies.

In RAYSAW, the light ray is replaced by a simulated band saw blade. Instead of the light rays emanating from viewpoint, the band saw blade "rays" emanate from a line parallel to the longitudinal axis of a log. The series of intersection points with the log and defects define the edge and defect points of a board. RAYSAW processes 3D log data collected using a three-head high- resolution laser-scanner and predicted internal defect data based on log surface defect indicators (Thomas 2008, 2009). The ability to process the 3D log data on a computer allows researchers to examine the impact of various sawing practices and different log quality and shape characteristics on lumber grade and value recovery. Once this technology is industrialized, it promises to improve grade recovery in hardwood sawmills. Recent advances in image processing have resulted in methods capable of detecting external log defects in the 3D laser data cloud (Thomas et al. 2006, Thomas and Thomas 2011). To make image data usable, the incoming 3D laser data are first processed to remove outlier points and fill areas of missing data using surrounding area information. Figure 1 shows a sample log from a laser-scanner as a dot cloud image.

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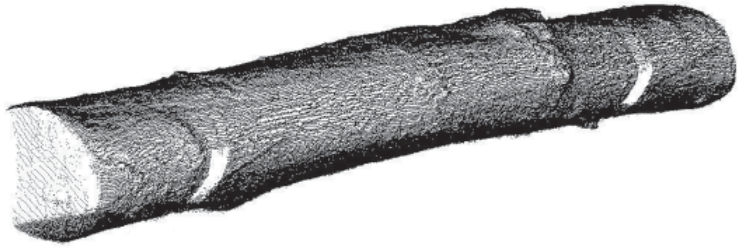

Figure 1.—Sample dot cloud image of a 3D laser-scanned red oak log.

Several simulators and a computerized sawing system for hardwoods have been developed in recent years. One of the first was a mathematically based hardwood log sawing program developed at the Forest Products Laboratory (FPL), in Madison, WI (Richards et al. 1979). The FPL log sawing program processed rough geometric log shape data (small- and large-end diameters, taper, sweep, and crook) and defect data. Defect data were manually placed on the log and internally modeled as a conic shape with the tip at the log center and the open end of the cone terminating inside or just outside the log surface. The FPL program would examine 12 different starting rotation degrees and do a complete sawing solution for each starting position using the same sawing pattern. The FPL sawing program was not user-interactive and simply provided end results based on the input log data and sawing specifications.

Later programs such as GRASP (Occeňa and Schmoldt 1996) were interactive and allowed users to guide the sawing process. The input data for GRASP are in a complete wire-frame form generated from CT scan data and digitized log coordinates. Log defects for GRASP were reconstructed using CT cross-sectional profiles and were modeled as separate solids within the wire-frame log representation. GRASP required the use of a third-party 3D computer-aided modeling program.

Perhaps the most advanced log sawing system is the one developed at West Virginia University (WVU) by Lin et al. (2011). Their sawing system processes summarized 3D laser-scan data and inferred internal defect shape and position data (Thomas 2008, 2009). The 3D laser-scan data are summarized to a circular single scan line for every foot of log length. The WVU system was not developed so much as a simulator but as a real-time system for determining the optimal breakdown of hardwood logs. As such, their system includes modules for grading lumber and for optimal edging and trimming operations. However, their sawing system uses a circular log shape model that prevents the system from accurately sawing elliptical or irregularly shaped logs.

RAYSAW was designed to use the native high-resolution data format directly from a laser log scanner. As such it processes true log shape data accurately to the nearest 1/16 inch. RAYSAW is a non-interactive, non-optimizing sawing simulator that determines the grade recovery given a log's shape and size, its defects, a sawing pattern, and a starting rotational degree. The starting rotational angle defines the starting position for a log. As in the Lin et al.'s (2011) sawing system, RAYSAW uses the internal defect prediction models developed by Thomas (2008, 2009) to determine internal defect shape and position. Combining the external laser imagery, surface defect locations and sizes, and predicted internal dimensions yields a 3D view of the log complete with external and internal defect data. This provides a near ideal data platform for conducting sawing research. And it allows the impact of alternative processing strategies given specific log features to be evaluated with respect to grade recovery. By using high-resolution data, RAYSAW generates accurate and realistic board profile data, from which accurate volume information can be calculated. This paper describes RAYSAW's mathematical basis and the system's sawing processes.

METHODS

The quality of the sawing solution depends on the computer model of the log being as accurate as possible. Abstractions and generalizations of log shape and log characteristics can result in less accurate solutions. The log surface is represented by a series of scan lines 1/16 inch apart that encircle the log. Each scan line is composed of 200 to 500 points depending on log circumference with smaller logs having fewer surface points. Outliers are statistically defined as any data point that is numerically distant from the rest of the data. In the log data, outliers are typically caused by the supports that hold the log during scanning, loose or dangling bark, and laser reflections off airborne dust. Outliers are removed from the original data by statistically comparing the location of points to neighboring points. The second step is filling in any missing data points to ensure a completely defined surface. Missing data points are commonly caused by outlier removal or by surface shadowing by the log supports and dangling bark. Missing data points are filled in using an average of neighboring points.

After the log data are cleaned of outliers and missing data points are filled, the external and internal defect representations can be added. External defect data consist of surface length, width, rise, and position (angle and distance from large end). The external defect data can be supplied by the automated defect detection software (Thomas et al. 2006, Thomas and Thomas 2011), or from a manually recorded log diagram. A log diagram records log shape and size as well as the position and type of all surface defects (Bulgrin n.d.). Internal defect features are generated using a series of prediction models (Thomas 2008, 2009). These models were developed using multiple linear regression methods to determine the correlations among external defect indicators such as log diameter, defect width, length, and rise to internal features such as encapsulation depth, total depth, penetration angle, and cross-sectional dimensions. The models were created by analyzing 842 red oak (*Quercus rubra* L.) and 1,000 yellow-poplar (*Liriodendron tulipifera* L.) defect samples collected from logs that were harvested from three sites in central Appalachia. Using the prediction models. an internal log defect representation is created. All defects have eight sides and two segments: internal endpoint to midpoint, and midpoint to external endpoint (Fig. 2). In instances where the defect has been encapsulated by clear wood, the external defect endpoint begins at the predicted beginning of the defective wood. The defect surface is modeled as a series of facets or triangles as shown in Figure 2.

In ray-tracing, a ray of light is traced from the observer back into the scene. As the ray hits objects, points and reflections are registered. For sawing a log, the ray-tracing process is greatly simplified because we are interested only in recording the points of intersection. While conventional ray-tracing has a single observer point, ray-tracing based sawing uses a line of starting points corresponding to the track of the saw along the log's length. For log sawing, the process of ray-tracing is further simplified to use two different intersection formulae. The first is a simple line intersection formula that locates the board edges. Each scan line around the circumference of a log at a given longitudinal point consists of 200 or more data points. Figure 3 shows the points of a single scanned line of a sample log and the outline of an internal defect. Line segments are defined between adjacent points

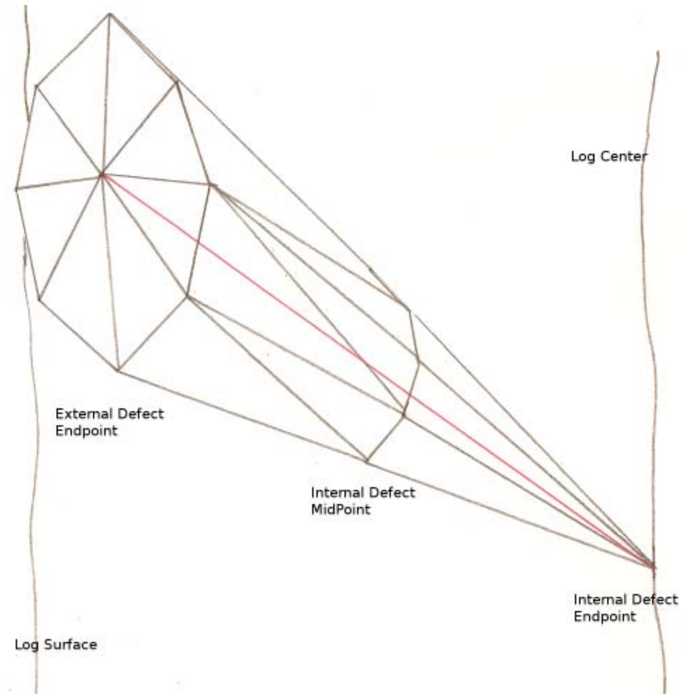

Figure 2.—Computer modeled internal and external representation of a log defect.

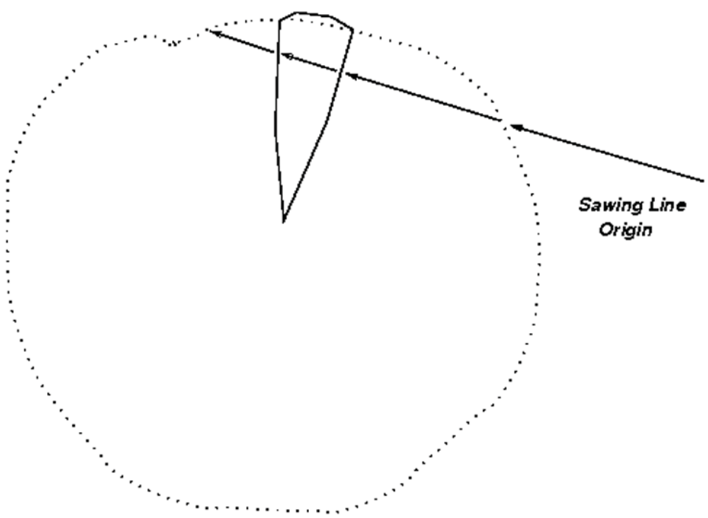

Figure 3.—Ray-traced sawing diagram of a log cross-section with an internal defect.

of a single scan line of a log. The equation for a sawing line S and a line segment L that connects two adjacent points in the scanned log circumference, where S has two points A and B, and L two points C and D are:

$$S = A + u_a(B - A)$$
$$L = C + u_b(D - C)$$

Solving for the intersection of point of S and L gives the following equations:

$$Ax + u_a(Bx - Ax) = Cx + u_b(Dx - Cx)$$
$$Ay + u_a(By - Ay) = Cy + u_b(Dy - Cy)$$

Solving for u_a and u_b:

$$u_a = \frac{(Dx - Cx)(Ay - Cy) - (Dy - Cy)(Ax - Cx)}{(Dy - Cy)(Bx - Ax) - (Dx - Cx)(By - Ay)}$$

$$u_b = \frac{(Bx - Ax)(Ay - Cy) - (By - Ay)(Ax - Cx)}{(Dy - Cy)(Bx - Ax) - (Dx - Cx)(By - Ay)}$$

The intersection point can be determined via substitution as:

$$x = Ax + u_a\ (Bx - Ax)$$
$$y = By + u_b\ (By - Ay)$$

Using the above equations, all log circumference line segment intersections with the sawing line are calculated. By moving the saw line along the length of the log, the entire board is "sawn" from the log. Because the saw line moves from scanned slice to scanned slice, the points and line are always coplanar, thus we need only consider two dimensions. The above equations also are used to detect when a saw line intersects a previous saw line. When this situation occurs, an edged, rather than wane edged, board is produced.

Detecting the intersection of the saw line with defects and generating the respective defect outline on the board's surfaces is more complex. The defects are modeled by a set of triangles, where the three points of the triangle define a plane. Thus, a line and plane intersection equation is used. Given a defect facet F with the normal vector n indicating the direction of F, and a saw line vector s, respectively. First, determine the vector w, the difference between n and s.

$$w = n - s$$

The next step is finding r, the distance from the origin of s to the intersection point on the facet.

$$r = \frac{-n \cdot w}{n \cdot s}$$

Adding s to the direction vector u by the distance r gives the intersection point P.

$$P = s + r * u$$

The above equations will find the intersection of the saw line s and the facet F. However, because F defines a plane, the next step is to determine if the intersection lies within the three points, Fa, Fb, and Fc that define the facet. Given the vectors:

$$U = Fa \rightarrow Fb \qquad\qquad V = Fa \rightarrow Fc$$

Determine the following dot products:

$$UU = U \cdot U \qquad UV = U \cdot V \qquad VV = V \cdot V$$

Next, find the vector from Fa to the intersection point P:

$$W = Fa \rightarrow P$$

Then, determine the following dot products with the vector W:

$$WU = W \cdot U \qquad\qquad WV = W \cdot V$$

Finally, determine the unit vector distances of the intersection point from the points Fb and Fc using the dot product values.

$$Q = \frac{UV * WV - VV * WU}{UV * UV - UU * VV}$$

$$T = \frac{UV * WU - UU * WV}{UV * UV - UU * VV}$$

If either Q or T is less than 0 or greater than 1, then the intersection lies outside of the facet, and the sawline does not intersect that portion of the defect.

As the sawing line moves along the length of the log, RAYSAW stores the distance of all intersects with the log surface, other sawlines, and defects. The distance data are processed such that a virtual board face with defects is produced. For example, Figure 3 shows a sawline intersecting a log cross section. The distance from the origin where each intersection occurs and the type of object (defect or log) intersected is recorded. Two passes of the sawing line at different cutting depths yields a complete board. RAYSAW can produce board data compatible with the ROMI rough mill simulator (Weiss and Thomas 2005) or the UGRS hardwood lumber grading and remanufacturing program (Moody et al. 1998).

RESULTS

As a demonstration of RAYSAW and the internal prediction models, the red oak log shown in Figure 2 was sawn with the sawing pattern shown in Figure 4. For this example, the log was sawn on a portable bandsaw mill. The sawing pattern and rotational positions were then reproduced in the sawing pattern for RAYSAW. The log was sawn into eight boards and a 2.125 by 5.875 inch cant. In the interest of brevity, only the first boards from sawn faces 1 and 3 are examined. Sawing started with a slab and a board being removed from face 1 (labeled "Board 1" in Figure 4). A photograph of the actual board and the computer predicted board are shown in Figure 5. Next, a slab is removed from face 2. From face 3 a slab and three boards are sawn. The outermost board sawn and the computer predicted board from this face are shown in Figure 6 (labeled "Board 2" in Figure 4).

There are two basic types of errors: missed defects and false-positive defects. Missed defects are actual defects whose occurrence the models did not predict. False-positive defects are ones that were predicted, but did not actually exist. For those defects predicted that did actually exist, there are two additional types of errors: positional and dimensional. Positional error is the distance between centers of the actual and predicted defect centers. Dimensional error is the difference between actual and predicted defect lengths and widths.

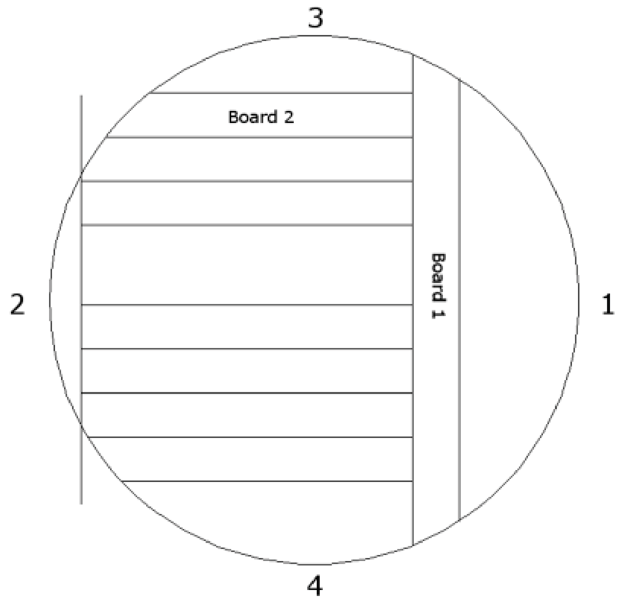

Figure 4.—Sawing pattern used to process log shown in Figure 1. Boards named are displayed in Figures 5 (Board 1) and 6 (Board 2). Faces are labeled by sawing sequence.

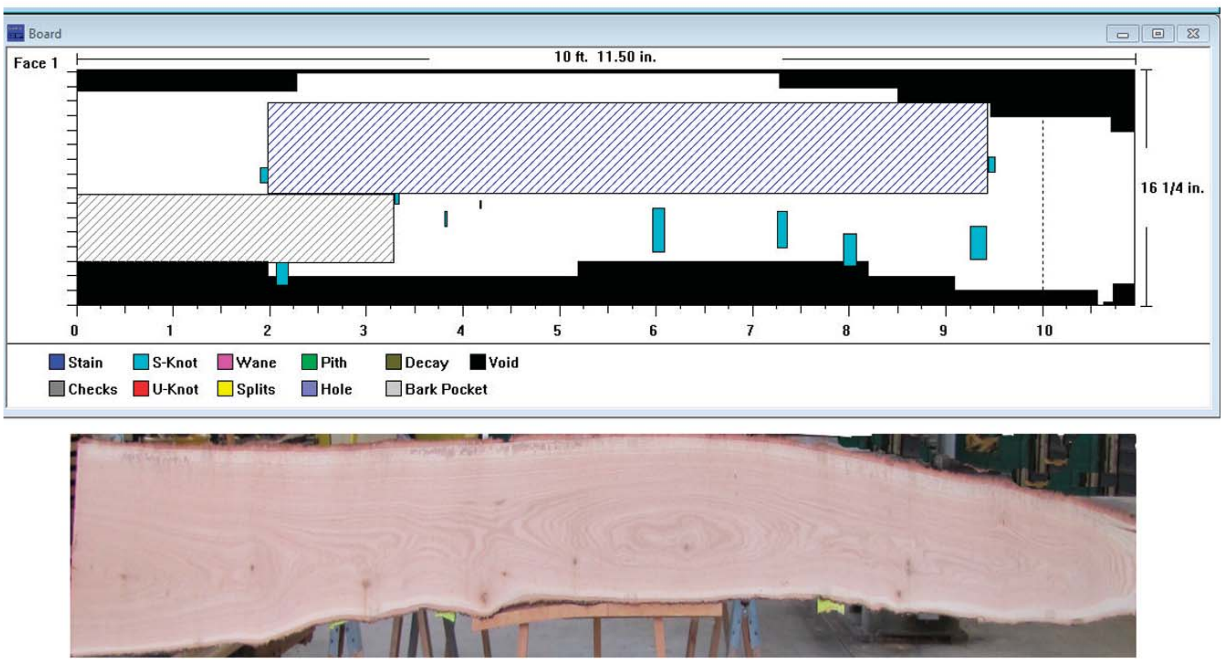

Figure 5.—Computer generated and actual board cut for Board 1.

On Board 1, there are a total of 11 defects. Of these, the internal prediction models predicted the occurrence of eight, missing three. In addition, the models predicted two false-positive defects. The average positional error for Board 1 was 3.64 inches and the average length and width dimensional error was 1.04 and 0.93 inches, respectively. For Board 2, the models predicted the occurrence of two of four total defects. There was one false-positive defect prediction. The average positional error for Board 2 was 3.63 inches and the average length and width dimensional error was 1.50 and 0.63 inches, respectively. Overall, the average positional error was 3.64 inches and the average length and width dimensional error was 1.13 and 0.87 inches, respectively.

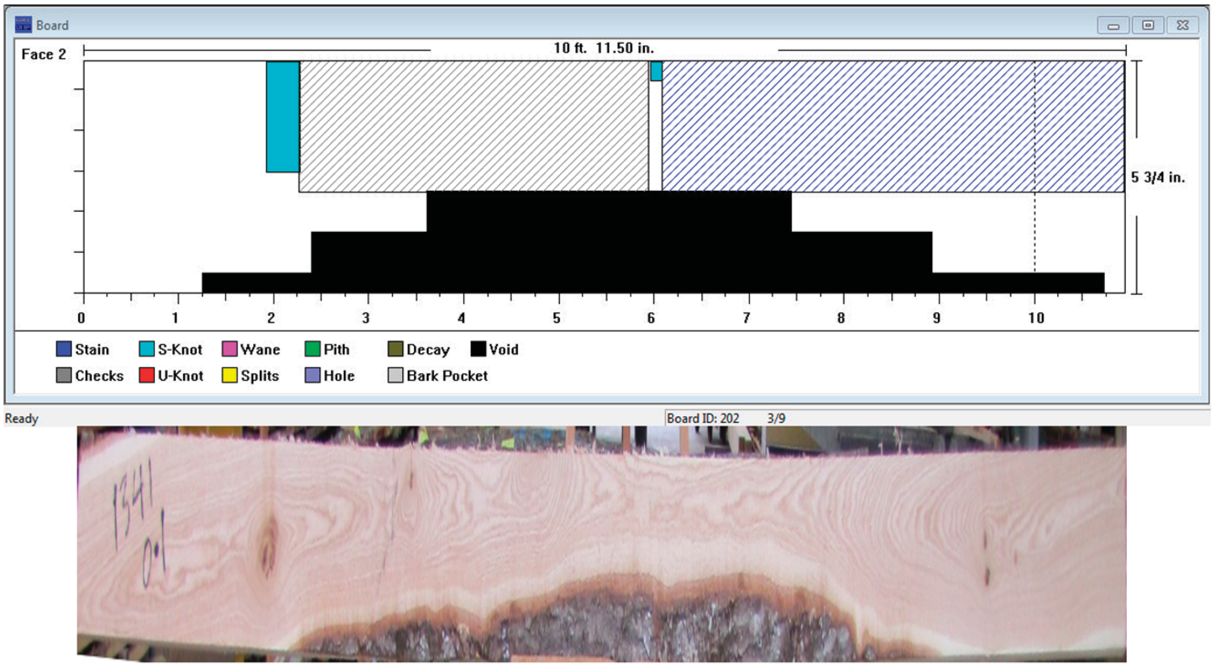

Figure 6.—Computer generated and actual board cut for Board 2.

In a further study, the accuracy of the red oak prediction models were examined by scanning a set of three logs and predicting the occurrence of knot defects on the sawn board faces (Thomas 2011a). The logs were then sawn on a portable sawmill to replicate RAYSAW's sawing parameters and log positioning. The study found that the models accurately predicted approximately 80 percent of all knot-type defects. The prediction models accurately placed internal knot defects with a median positional error of 0.875 inch. The error was measured from the center of the actual defect to the center of the predicted defect. In most cases the predicted and actual defect areas often overlapped, potentially minimizing the impact of defect location error on predicted grade and yield. For 32.8 percent of predicted internal defects, the difference between predicted and actual defect area was 2.5 in^2 or less, with an overall median size error of 4.94 in^2. Although this error may sound large, consider a knot with an actual size of 3 by 3 inches and a predicted size of 3.7 by 3.77 inches, which has an error of 0.7 by 0.77 inches. This size error is 4.94 in^2 with a relatively small error in predicted defect dimensions. In addition, missing the location of a defect by 1 inch on a board is unlikely to lead to lower grading of the board, nor will it likely impact yield when the board is processed in the rough mill (Thomas 2011b).

DISCUSSION

Although the defect model predictions of location, width, and length seem acceptably small, a second study was conducted to determine if these errors have a significant impact on predicted lumber quality (Thomas 2011b). In this study, 26 red oak logs were scanned and their defect locations manually located and diagrammed. The internal prediction models were modified to generate internal defect measurement and location estimates that randomly varied between +/- mean absolute error (MAE) for each internal characteristic. A total of 30 random defect variations, as well as the normal variation and the normal +MAE, and normal –MAE, were generated, producing 33 defect variations for each scanned log. Each log was then sawn with four different sawing patterns and the resulting boards graded with the UGRS grading program (Moody et al. 1998). Overall, there were few significant differences among the random only sawn lumber sets. Within the 33 defect size variations sets, 8 of the 26 logs had no significant differences in lumber recovery, and 9 had five or less significant differences. The remaining nine sets had one or more sawing rotation where a defect variation resulted in a significant difference with all other lumber sets. Some of the significant differences between the random variation sets were linked to logs that had knot clusters or more than an average number of bark distortions. Knot clusters and bark distortions have some of the weakest correlations to internal features and thus had a greater variability in internal size and position in the random variation sets (Thomas 2008, 2009). The random defect variation sets are more likely true to reality than the worst (+MAE) and best (-MAE) case defect datasets. When the worst and best defect sets were combined with the random variation defect sets, significant differences were observed between the worst case and the random variation defect sets. Also, as expected, there were significant differences between the best and worst case defect size variations.

SUMMARY

RAYSAW was developed for research purposes, specifically to provide a means of testing the internal defect prediction models. As such, RAYSAW lends itself well to answering questions about the impacts of various sawing practices and log quality and shape characteristics on grade and value recovery of hardwood logs. For example, an elliptical log could be processed using different patterns to determine if log rotation has a significant impact on recovery. RAYSAW processes high-resolution laser-scan data and reports accurate sawing and waste volumes. The simulator saws to a pre-defined pattern that specifies the sawing line and board thickness. The boards produced by RAYSAW can be viewed graphically, graded to NHLA rules, and processed into rough dimension parts using freely available software. A graphical user interface for designing sawing patterns is available. Additional internal log defects are being collected to refine internal defect modeling especially for those defects with low internal to external feature correlations, such as knot clusters, and light and medium distortions.

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RELATIONSHIP OF MINERAL STAIN IN RED OAK TO GROWTH SITE VARIABLES

Brian H. Bond and Lyn M. Resler[1]

Abstract.—The presence of mineral stain in red oak (*Quercus rubra*) significantly reduces the value of the forest products that contain it. Mineral stain is also associated with reductions in the quality of the material. Although poor site quality has been cited as a probable cause of mineral stain in red oak, little is known about the specific site variables associated with site quality and high mineral stain severity. The goal of this study is to better understand environmental, geographic, and spatial correlates of mineral stain in red oak at eight study sites throughout the Appalachian Mountains of Virginia and West Virginia. Specific objectives were to (1) characterize the presence and severity of mineral stain in red oak trees at selected study sites, and among geographic locations; (2) determine the strongest site quality correlates (e.g., slope aspect, soil moisture, harvesting history) of mineral stain in red oak using field sampling and geospatial techniques; and (3) develop a model to predict mineral stain in red oak. Geographic and growth site factors were selected through a literature search and a survey of foresters who purchased stands for harvesting. Then, the presence and severity of mineral stain in red oak were sampled at eight locations and correlated to growth site variables collected in the field and derived from spatial datasets. A statistical model was developed to predict mineral stain presence. It was determined that elevation, slope angle, solar radiation, flow accumulation, and cardinal direction contribute the most to the presence or absence of mineral stain in red oak for the sites studied. The values of the model coefficients suggest that the probability of staining is highest when the tree is on a relatively flat part of the ground, which receives more water and little sunlight to evaporate the moisture. Although our model does explain a large amount of the important variables related to the presence and absence of mineral stain, it is clear that some important variables were not included or that some variables measured did not contain enough contrast to provide a clearer picture of their contribution.

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POTENTIAL FOR APPALACHIAN HARDWOOD PRODUCT UTILIZATION IN AFFORDABLE HOUSING PROJECTS

David B. DeVallance, Shawn T. Grushecky, and Greg Estep[1]

Abstract.—The emerging green building sector has potential for becoming a significant market opportunity for Appalachian hardwood manufacturers. The amount of harvested and utilized Appalachian hardwoods will be impacted by the amount of hardwood products produced for green building projects. The affordable housing sector in the United States represents an important market for wood products. Many states, cities, and nonprofits are encouraging, and in many cases requiring, the use of green building practices under their affordable housing and financial incentive programs. Many of these green building practices differ from nationally recognized green building programs (e.g., Leadership in Energy and Environmental Design [LEED], National Association of Home Builders [NAHB]). Furthermore, there is little information related to how wood products, specifically those manufactured from Appalachian hardwoods, fit within the context of the varying green building incentive programs. The purpose of this study was to evaluate the use of green certified and noncertified wood materials in affordable housing projects within Central Appalachia. A randomized sampling method was used to select builders to survey within the region. Additionally, members of the Federation of Appalachian Housing Enterprises (FAHE) were surveyed separately. We report findings related to what type of green certified and noncertified wood products are used in affordable housing projects within Central Appalachia and will report on builders' perceptions of the local availability of certified wood products.

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SILVICULTURE

INFLUENCE OF PLANTING STOCKS ON THE SURVIVAL AND GROWTH OF NUTTALL AND CHERRYBARK OAK PLANTED ON LANDS DAMAGED BY HURRICANE KATRINA

Derek K. Alkire, James C. Rainer, Andrew B. Self, Andrew W. Ezell, Andrew J. Londo, and Emily B. Schultz[1]

Abstract.—Bare-root, container, and root production method (RPM™) seedlings of Nuttall oak (*Quercus texana* Buckley) and cherrybark oak (*Q. pagoda* Ell.) were planted on lands damaged by Hurricane Katrina in southern Mississippi to compare the height growth, groundline diameter (GLD) growth, and survival of the different planting stocks. Two study areas were divided into three replicates containing six treatment combinations with 100 seedlings per replicate. Tree shelters were used on half of the bare-root seedlings to determine their effect on height, GLD growth, and survival of the seedlings. Height and GLD growth were greater in RPM™ seedlings compared to bare-root or container seedlings after one growing season. Bare-root seedlings exhibited greater height and GLD growth than container seedlings. Tree shelters increased height growth of bare-root seedlings; however, sheltered bare-root seedlings exhibited less GLD growth than unsheltered seedlings. Cherrybark oak exhibited greater height growth than Nuttall oak, whereas Nuttall oak exhibited greater GLD growth than cherrybark oak across all planting stocks. There was no significant difference among the planting stocks after the first growing season.

INTRODUCTION

Among the many benefits of bottomland hardwood forests are flood protection, increased groundwater storage, increased soil productivity, and reduced nutrient runoff (Sparks 1995). However, oak regeneration on these mesic bottomland hardwood sites has proven to be problematic (Clatterbuck and Meadows 1993, Janzen and Hodges 1987, Johnson et al. 2002, Loftis and McGee 1993, Lorimer 1993). Failure can be attributed to inadequate regeneration before harvest, predation, herbivory, and the inability of seedlings to compete with other vegetation for resources such as light and water (Allen et al. 2001, Loftis 1983, Lorimer 1989, Stanturf et al. 2001). Environmental factors such as extended drought and flooding also contribute greatly to poor seedling survival and growth (Allen and Burkett 1996, Gardiner et al. 2004, Kennedy and Johnson 1984). Bottomlands commonly have an adequate supply of nutrients and water, which generally favors species with rapid growth rates and thus compounds the problem of inadequate oak regeneration (Hicks 1998).

To solve the problem of inadequate oak regeneration, many private landowners have elected to use artificial regeneration. The goal of planting seedlings on previously forested areas is to accelerate natural succession (Stange and Shea 1998). However, in large-scale plantings of seedlings in bottomland hardwoods, mortality is often high after planting (Cleveland and Kjelgren 1994, Schweitzer and Stanturf 1997), resulting in planting failures (Patterson and Adams 2003). Poor survival of oaks has been linked to factors such as slow growth, rapid growth of competing vegetation, poor planting, and poor seedling quality (Johnson et al. 1986, McGee and Loftis 1986, Pope 1993,

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Russell 1971). Potentially high mortality rates underscore the importance of matching species with site, planting vigorous seedlings, and using proper planting methods.

In 2005, Hurricane Katrina destroyed thousands of hectares of bottomland hardwood forest in Mississippi. Natural regeneration on hurricane-disturbed lands, like that on harvest-disturbed lands, may result in site-dominating species that are undesirable for landowner objectives (Aust et al. 2006, Battaglia et al. 1999, Peterson and Pickett 1995). The bulk of these undesirable species may be light-seeded species such as sweetgum (*Liquidambar styraciflua* L.) and American elm (*Ulmus americana* L.) (Allen 1990). Desirable species such as oaks have been shown to make up less than 10 percent of regeneration when a stand is allowed to regenerate naturally (Johnson 1984). Thus, due to the potential lack of desirable heavy-seeded species such as oaks (*Quercus* spp.), seedlings must often be planted to achieve reforestation objectives (Allen 1990).

Costs associated with reforestation of these lands can be excessive for nonindustrial private landowners. Federal programs such as the Wetlands Reserve Program (WRP) and Conservation Reserve Program offer cost-share incentives to offset the expense of restoring bottomland hardwoods (Williams and Craft 1998). However, Schweitzer and Stanturf (1997) found that only 9 percent of the total reforested land in Mississippi planted in the WRP program met the Natural Resources Conservation Service requirement of at least 308 hard-mast stems per ha in 3-year-old stands. A possible explanation for the failures could be that the program uses direct seeding and bare-root seedlings. The use of different planting stocks may increase survival rates on these reforested lands. However, biological and economic outcomes of artificial regeneration are not fully understood in terms of which species or planting stocks will be most successful or cost-effective.

This study focused on reforestation of Hurricane Katrina-damaged lands and attempted to add to the body of knowledge about planting stock comparisons and proper stocking of oaks on a site. It was a valuable opportunity to study management practices following a major disturbance event and provide managers and private landowners with recommendations for future work. The overall objective of this study was to determine the effect of species, planting stock, and tree shelters on survival and growth of Nuttall (*Quercus texana* Buckley) and cherrybark (*Q. pagoda* Ell.) oak seedlings planted on hurricane-damaged lands. The planting stocks were: 1-0 bare-root, containerized (409.68 cm^3 Nuttall, 331.84 cm^3 cherrybark), and 11.356-L root production method (RPM™) (Forrest Keeling Nursery, Elsberry, MO) seedlings. Specific objectives were: (1) to compare overall height growth and groundline diameter (GLD) growth of Nuttall and cherrybark oak 1 year after planting, (2) to compare overall survival of the three different planting stocks for Nuttall and cherrybark oak 1 and 2 years after planting, and (3) to evaluate the effect of tree shelters on survival and growth rates of bare-root Nuttall and cherrybark oak seedlings.

STUDY AREA

Two study areas on bottomland hardwood sites damaged by Hurricane Katrina were chosen for reforestation and evaluation. The two sites were selected for uniformity of soil and terrain properties. One area, known as the Norris tract, is located in section 3, T3S R12W in Stone County, Mississippi. The area received a salvage harvest following Hurricane Katrina. Site preparation on the area included the use of a bush hog to mow down vegetation and a bulldozer to clear stumps. Dominant vegetative species on the site before the first growing season were blazing star (*Liatris spicata* Willd.), boneset (*Eupatorium* spp. L.), partridge pea (*Chamaecrista fasciculata* Michx.), broomsedge (*Andropogon virginicus* L.), blackberry (*Rubus* L.), rush (*Juncus* L.), goldenrod (*Oligoneuron* Small), gallberry (*Ilex* Chapm.), and hoary mountain mint (*Pycanthemum incanum* L). Woody species present on the area before the salvage cut included blackgum (*Nyssa sylvatica* Marsh.), sweetgum, red maple (*Acer rubrum* L.), American beech (*Fagus grandifolia* Ehrh.), black cherry (*Prunus serotina* Ehrh.), persimmon (*Diospyros virginiana* L.), water oak (*Q. nigra* L.), winged sumac (*Rhus copallina* L.), loblolly pine (*Pinus taeda* L.), and swamp chestnut oak (*Q. michauxii* Nutt.). Based on soil samples, pH across the site averaged 4.7, which is within the desired pH range for cherrybark and Nuttall oak.

The second area, known as the Garretson tract, is located in section 12, T3N R6W in Greene County, Mississippi. Following Hurricane Katrina, a salvage cut was conducted on the area. Stumps too large to be moved by a bulldozer were left, and smaller stumps were removed. The dominant woody species on the area before the salvage cut was swamp chestnut oak. Other tree species present on the area prior to the salvage cut were cherrybark oak, willow oak (*Q. phellos* L.), water oak, hickory (*Carya* spp. Nutt.), white oak (*Q. alba* L.), American beech, red maple, elm (*Ulmus* spp. L.), American hornbeam (*Carpinus caroliniana* Walter), persimmon, sweetgum, and Chinese tallow tree (*Sapium sebiferum* L.). Vegetation on the area consisted of Carolina horsenettle (*Solanum carolinense* L.), blackberry, American pokeweed (*Phytolacca americana* L.), hogwort (*Croton capitatus* Michx.), foxtail (*Alopecurus* spp. L.), Japanese climbing fern (*Lygodium japonicum* Murr.), hempvine (*Mikania scandens* Willd.), smooth greenbrier (*Smilax glauca* Walt.), morningglory (*Ipomoea spp*. L.), and woodoats (*Chasmanthium* spp. L.). Soil pH across the site varied from 4.6 to 5.0, which is within the desired pH range for cherrybark and Nuttall oak.

METHODS

Experimental Design and Demarcation

Each of the two study areas was divided into three replicates. Each replicate was located on uniform areas across the site. Six hundred seedlings were planted in each replicate, for a total of 1,800 seedlings planted per site.

On the Garretson tract, two of the replicates were 40 m by 158 m. These replicates consisted of 12 rows of 50 seedlings each. Because of a large flooded area, the third replicate had a different configuration. It was 46 m by 183 m and consisted of 9 rows of 50 seedlings, 5 rows of 25 seedlings, 1 row of 15 seedlings, and 1 row of 10 seedlings.

On the Norris tract, the first replicate was 91 m by 82 m, consisting of 20 rows of 20 seedlings, and 8 rows of 25 seedlings. The second replicate was 76 m by 82 m, consisting of 24 rows of 25 seedlings. The third replicate was 140 m by 82 m, consisting of 21 rows of 25 trees, 1 row of 20 trees, and 3 rows of 10 trees.

The experimental unit was the plot, which has a unique combination of planting stock, species, chemical treatment, and tree shelter application (n=8). The experimental units in each replication were as follows: 50 bare-root Nuttall oak with herbicide treatment and tree shelters, 50 bare-root Nuttall oak with herbicide treatment, 50 bare-root cherrybark oak with herbicide treatment and tree shelters, 50 bare-root cherrybark oak with herbicide treatment, 100 containerized Nuttall oak, 100 containerized cherrybark oak, 100 RPM™ Nuttall oak, and 100 RPM™ cherrybark oak. The location of the six planting stock and species combinations was randomly assigned within each replicate.

All trees were planted on 3.048 m by 3.048 m spacing. The location of each tree to be planted was marked with a 92-cm colored pin flag. Each planting stock and species combination was denoted by a different-colored pin flag. Row ends were marked with a 1-m section of 0.94-cm steel reinforcing bar and flagging. An aluminum tag with the row number was attached to the bar.

Treatments

Protex® tree shelters (Norplex Inc., Auburn, WA) 92 cm tall were placed on half of the bare-root seedlings in March 2010 after initial measurements were taken. All bare-root seedlings received a pre-emergent banded herbicide treatment of Oust® XP (DuPont, Wilmington, DE) (146.16 ml sprayed per ha) 1 week after planting. The herbicide was applied over the top of seedlings by using a backpack sprayer to apply a 1.52-m swath with the seedling as the center of the spray swath.

Seedling Establishment

In early February 2010, the RPM™ seedlings were planted by a contractor. The seedlings were produced from seeds collected in Louisiana and Mississippi and were grown by using the RPM™ at a nursery in Ravenel, South Carolina. Half of the seedlings were planted by using an ASV RC-30 rubber-track loader (ASV, Inc., Grand Rapids, MN) with an auger; the other half were planted with planting shovels. Crews were monitored by a Mississippi State University graduate student to ensure the trees were being planted correctly. Seedlings had an initial average height of 125.5 cm and GLD of 16.5 mm.

Bare-root and containerized seedlings were planted in mid- to late-February 2010 by Mississippi State University personnel. Containerized seedlings were from Rennerwood Inc. in Tennessee Colony, Texas. Bare-root seedlings were from the Molpus Woodlands Group tree nursery in Elberta, Alabama. Bare-root and container seedlings were planted by hand with planting shovels. Bare-root seedlings had an initial average height of 57.2 cm and GLD of 8.1 mm. Containerized seedlings initially averaged 59.7 cm in height and 6.9 cm in GLD.

Seedling Measurements

Height and GLD of each seedling were measured in March 2010 and October 2010. Tree heights were measured in centimeters with a meter stick and were recorded as the height from ground level to the terminal bud.; Digital calipers were used to measure GLDs in millimeters just above the root collar. Survival of seedlings was recorded monthly from May through October 2010 for the first year, and will be recorded at the end of the October 2011 growing season. If ocular observation determined a seedling to be dead, the cambial layer was examined to confirm seedling survival status.

Analysis

Analysis of variance was performed using PROC GLM in SAS software version 9.2® (SAS Institute, Cary, NC). Response variables were height growth, GLD growth, and survival. Means separation of first-year survival, height growth, and diameter growth was analyzed using least square differences (LSD). During analysis of survival data, a histogram of residuals was made. Residuals were not mounded and symmetric, so an analysis of plot survival percentage with an arcsine transformation was performed. Differences among treatments were tested at $\alpha = 0.05$.

RESULTS AND DISCUSSION

Overall Survival

A significant difference between sites in this study was not observed; therefore, survival data were analyzed as a whole and not by site. This outcome contrasts with that reported by Ezell and Catchot (1998), who showed that site can have an effect on hardwood seedling survival.

First-year survival for Nuttall oak was higher than survival for cherrybark oak, although cherrybark oak survival was 98.1 percent and the difference was only 1.1 percent across all planting stocks. These results agree with Self et al. (2009), who found Nuttall oak exhibited higher survival than cherrybark oak on a saturated site in Louisiana; however, the difference in this study was much less than they observed. The overall high survival rates are consistent with other studies, including those conducted in a nursery setting (Jacobs 2003).

No significant differences were observed in survival among the three planting stocks. Observed survival of container seedlings (99.4 percent) did not differ from that of bare-root or RPM™ planting stocks (98.0 percent and 98.6 percent, respectively). All three planting stocks exhibited excellent survival rates that would provide adequate stocking in reforestation attempts.

Container Nuttall oak, container cherrybark oak, bare-root Nuttall oak, and RPM™ Nuttall oak all exhibited a survival rate greater than 99 percent. Survival of all other species/planting stock combinations was greater than 97 percent. Cherrybark oak bare-root seedlings exhibited the least survival at 97.1 percent, which is still very high.

Although stem dieback and slow initial growth may result in low survival of bare-root seedlings (Rathfon et al. 1995), the results from this study indicated otherwise. Bare-root seedlings had survival rates of 99.0 percent and 97.1 percent for Nuttall and cherrybark oak, respectively. Bare-root Nuttall oak exhibited only 0.1 percent lower survival than containerized Nuttall oak, and 0.5 percent lower survival than RPM™ Nuttall oak. Bare-root cherrybark oak seedlings exhibited lower survival rates than containerized and RPM™ cherrybark seedlings, but the difference was less than 3 percent in both cases.

Lower second-year survival is expected across all treatments based upon visual observation made throughout the 2011 growing season. High temperatures, a lack of precipitation, and herbivory are the primary reasons for the mortality expected during the 2011 growing season. Although survival across planting stocks is assumed to be lower in year 2, differences in survival rates between planting stocks in year 2 are expected to resemble those in year 1.

Survival: Sheltered vs. Unsheltered Bare-root Seedlings

No significant difference in survival was detected between sheltered and unsheltered seedlings, which exhibited excellent survival levels (97.3 percent and 98.7 percent, respectively). Survival was greater in unsheltered Nuttall oak seedlings (99.6 percent) than in Nuttall oak seedlings with shelters (98.4 percent). Unsheltered cherrybark oak seedlings exhibited a higher survival rate at 98.0 percent compared to sheltered cherrybark oak seedlings, which had the least survival of the species/shelter combinations at 96.3 percent. Sheltered and unsheltered Nuttall oak exhibited greater survival than sheltered and unsheltered cherrybark oak. Although significant differences were observed, survival was excellent regardless of species/shelter combination.

Overall Height Growth

Analyses of growth data were performed only on seedlings that did not exhibit dieback or resprout (n=3,017). Therefore, only seedlings exhibiting an increase in height or GLD were included in the analyses. It was concluded that seedlings not exhibiting an increase in height or GLD were masking the realistic growth potential of the seedlings (Self 2009).

Cherrybark and Nuttall oak height growth (16.1 cm and 15.3 cm, respectively) were not significantly different (Table 1). Average height growth was greater in RPM™ seedlings than in bare-root and container seedlings (26.3 cm, 10.7 cm, and 7.3 cm, respectively). Bare-root seedlings exhibited greater height growth than container seedlings, which is not typical (William and Stroupe 2002). However, similar results have been reported in one earlier study on the Yazoo National Refuge in Mississippi (Burkett et al. 2005). Results in this study could reflect the high quality of the bare-root seedlings, whose substantial number (average >8) of first-order lateral roots would allow allocation of resources to height growth. Another possible explanation is planting quality. Operational planters often tend to focus more on planting speed than planting quality, but in this study, great care was taken to plant all seedlings properly.

Table 1.—Average growth by species after one growing season on seedlings not exhibiting dieback/resprouts (all planting stocks and treatments)

Species	Height†	GLD
	---cm---	---mm---
Cherrybark oak	16.1 a‡	2.3 b
Nuttall oak	15.3 a	3.5 a

† Values are means of six replications.
‡ Means within a column followed by the same letter do not differ at α = .05.

The greatest height growth of all the species/planting stock combinations occurred in RPM™ cherrybark oak (28.7 cm), RPM™ Nuttall oak (23.8 cm), and bare-root Nuttall oak (13.0 cm) (Table 2). Establishment of an adequate root system before outplanting made RPM™ seedlings less susceptible to transplant shock than were other planted seedlings. Dey et al. (2004) reported comparable height growth in RPM™ oak seedlings in Missouri. Containerized cherrybark oak exhibited slightly greater height growth than bare-root cherrybark oak (8.1 cm and 7.8 cm, respectively); however, the difference was not significant (Table 2).

Table 2.—Average growth after one growing season based on seedlings not exhibiting dieback/resprouts (all treatments)

Species	Height†	GLD
	--cm--	--mm--
Cherrybark oak		
Bare-root	7.8 d‡	1.3 c†
Container	8.1 d	1.4 c
RPM™	28.7 a	3.7 b
Nuttall oak		
Bare-root	13.0 c	3.6 b
Container	6.3 e	1.9 c
RPM™	23.8 b	4.7 a

† Values are means of six replications.
‡ Means within a column followed by the same letter do not differ at α = .05.

Container Nuttall oak seedlings showed the least growth of the species/planting stock combinations. It is not typical for bare-root seedlings to outperform containerized seedlings although Self et al. (2009) observed bare-root seedlings exhibited greater height growth than containerized seedlings. In contrast, Rathfon et al. (1995) found no significant difference in height growth of bare-root and container red oak (*Q. rubra* L.) seedlings after one growing season. Height growth data were reported by site because of the statistical differences found between sites for height growth.

Height Growth Variation on the Garretson Tract

On the Garretson tract, RPM™ seedlings significantly outperformed both the bare-root and containerized seedlings in height growth (27.8 cm, 13.3 cm, and 8.8 cm, respectively). Other studies such as Shaw et al. (2003) reported similar results in which height growth of RPM™ seedlings exceeded that of bare-root and containerized seedlings.

The greatest height growth of any species/planting stock combination on the Garretson tract occurred in RPM™ cherrybark oak, RPM™ Nuttall oak, and bare-root Nuttall oak (30.2 cm, 25.1 cm, and 16.2 cm, respectively) (Table 3). Cherrybark oak bare-root and container seedlings exhibited similar height growths (9.6 cm and 9.5 cm, respectively). Container Nuttall seedlings exhibited the least height growth with only 7.2 cm of growth after the first growing season (Table 3).

Table 3.—Average height growth after one growing season based on seedlings not exhibiting dieback/ resprouts on the Garretson and Norris tracts (all treatments)

	----------Site----------	
	Garretson	Norris
Cherrybark oak		
RPM™	30.2 a†	27.1 a†
Bare-root	9.6 d	6.5 d
Container	9.5 d	5.6 d
Nuttall oak		
RPM™	25.1 b	22.8 b
Bare-root	16.2 c	5.8 d
Container	7.2 e	8.8 c

† Means followed by the same letter do not differ at $\alpha = .05$.

RPM™ cherrybark oak seedlings exhibited approximately 30 percent greater height growth than any other cherrybark oak planting stock (Table 3). Bare-root Nuttall oak outperformed container seedlings of both species. The Nuttall bare-root seedlings may have performed so well because they were well suited for the site. No significant difference was found in height and GLD growth by species, so species were not analyzed by site.

Height Growth Variation: Sheltered vs. Unsheltered Bare-root Seedlings on the Garretson Tract

Seedlings with tree shelters exhibited greater height growth than unsheltered bare-root seedlings on the Garretson tract (16.7 cm and 9.4 cm, respectively). Sheltered Nuttall oak seedlings had greater height growth than any other species/shelter combination (20.8 cm). Sheltered cherrybark oak exhibited slightly greater growth than either Nuttall or cherrybark oak without shelters (10.2 cm, 9.7 cm, and 9.0 cm, respectively), but the difference was not significant.

Height Growth Variation on the Norris Tract

When planting stocks of both species were combined for analysis, RPM™ seedlings exhibited greater height growth than bare-root or container seedlings (24.7 cm, 7.4 cm, and 6.2, respectively). Planting stock results for the Norris tract are consistent with results from the Garretson tract.

Table 4.—Average growth by species for sheltered and unsheltered bare-root seedlings after one growing season on seedlings not exhibiting dieback/ resprouts

Treatment	Height†	GLD
	---cm---	---mm---
Nuttall oak		
Shelter	17.0 a‡	3.1 b
No shelter	7.5 b	4.2 a
Cherrybark oak		
Shelter	8.5 b	1.3 c
No shelter	7.1 b	1.4 c

† Values are means of six replications.
‡ Means within a column followed by the same letter do not differ at $\alpha = .05$.

RPM™ cherrybark oak, RPM™ Nuttall oak, and bare-root Nuttall oak had the greatest height growth of any species/planting stock combination (27.1 cm, 22.8 cm, and 8.8 cm, respectively) (Table 4). Container cherrybark, container Nuttall, and bare-root cherrybark oak growth were not significantly different (6.5 cm, 5.8 cm, and 5.6 cm, respectively). Height growth of RPM™ cherrybark was significantly greater than that of other species/planting stock combinations (Table 3). The second-highest height growth occurred in RPM™ Nuttall oak. Other than RPM™ seedlings of both species, Nuttall oak bare-root seedlings significantly outperformed all other species/ planting stock combinations.

Height Growth Variation: Sheltered vs. Unsheltered Bare-root Seedlings

Sheltered seedlings exhibited greater height growth than unsheltered seedlings (13.6 cm and 7.3 cm, respectively). Shelters have been used in Europe for decades with great success (Morrow 1988), and, more recently, have been reported to provide beneficial increases in first-year height growth of seedlings in the United States (Bendfeldt et al. 2001, Conner et. al 2000). Thus, results of this study are consistent with earlier work in that shelters increased seedling height growth by nearly twofold. It is important to note that these results may be skewed slightly by the extraordinary height growth of sheltered Nuttall oak.

Sheltered bare-root Nuttall oak seedlings had at least twice the height growth of unsheltered Nuttall oak, sheltered cherrybark oak, and unsheltered cherrybark oak (17.0 cm, 7.5 cm, 8.5 cm, and 7.1 cm, respectively) (Table 4). Shelters have been known to increase height growth by as much as five times that of unsheltered seedlings (Potter 1987, 1988; Tuley 1985).

Height Growth Variation: Sheltered vs. Unsheltered Bare-root Seedlings on the Norris Tract

Sheltered seedlings exhibited greater height growth than unsheltered seedlings on the Norris tract (9.7 cm and 4.5 cm, respectively). Sheltered Nuttall oak seedlings had the greatest height growth of any species/shelter combination (11.9 cm) (Table 5). Sheltered cherrybark oak outperformed unsheltered seedlings of Nuttall and cherrybark oak (6.7 cm, 4.8 cm, and 4.1 cm, respectively) (Table 5). Unsheltered trees exhibited similar height growth rates and were not significantly different.

Table 5.—Average height growth by species for sheltered and unsheltered bare-root seedlings after one growing season on seedlings not exhibiting dieback/resprouts on the Norris tract

Treatment	Height†
	---cm---
Nuttall oak	
Shelter	11.9 a‡
No shelter	4.8 c
Cherrybark oak	
Shelter	6.7 b
No shelter	4.1 c

† Values are means of six replications.
‡ Means followed by the same letter do not differ at α = .05.

Height Growth Summary

Although height growth patterns on both sites were consistent, the amount of height growth varied by site (Table 6). Cherrybark oak had greater incremental growth than Nuttall oak. Bare-root seedlings outgrew container seedlings on both sites. Containerized seedlings exhibited the least height growth of the planting stocks in this study. Typically container seedlings have greater height growth than bare-root seedlings (Williams and Craft 1998). RPM™ cherrybark oak seedlings exhibited the greatest height growth of all species/planting stock combinations; container Nuttall oak seedlings exhibited the least height growth of all combinations. Bare-root Nuttall and cherrybark oak seedlings outgrew container Nuttall seedlings; however, their growth rates were not significantly different from container cherrybark seedlings even though they exhibited greater performance.

Table 6.—Average growth by site after one growing season on seedlings not exhibiting dieback/ resprouts (all planting stocks, species, and treatments)

	----------Site----------	
Growth	Garretson	Norris
Ht (cm)	12.7 a†	8.6 b
GLD (mm)	2.4 a	2.1 a

† Means within a row followed by the same letter do not differ at α = .05.

Overall GLD Growth

The data for GLD growth were not analyzed by site because the growth did not vary by site (Table 6). When data for both species were combined for analysis, RPM™ seedlings exhibited the greatest GLD growth of all the planting stocks (4.7 mm). Container seedlings exhibited significantly less GLD growth than bare-root seedlings (1.6 mm, 2.6 mm, respectively). Bare-root seedlings are generally expected to have less GLD growth than container seedlings (Rathfon et al.1995, Williams and Craft 1998, Williams and Stroupe 2002).

For all planting stocks, GLD growth was greater for Nuttall than for cherrybark oak (3.5 mm and 2.3 mm, respectively) (Table 1). The greatest amount of GLD growth occurred in RPM™ Nuttall oak, RPM™ cherrybark oak, and bare-root Nuttall oak (4.7 mm, 3.7 mm, and 3.6 mm, respectively) (Table 2), and that of RPM™ Nuttall oak was significantly greater than for any other species/planting stock combination. Bare-root cherrybark oak, container Nuttall oak, and container cherrybark oak seedlings exhibited similar GLD growth (1.3 mm, 1.9 mm, and 1.4 mm, respectively) (Table 2).

GLD Growth Variation: Sheltered vs. Unsheltered Bare-root Seedlings

When both species were combined for analysis, sheltered seedlings exhibited significantly less GLD growth than unsheltered seedlings (2.4 mm and 2.9 mm, respectively). Unsheltered Nuttall oak seedlings exhibited greater GLD growth than sheltered Nuttall oak seedlings (4.2 mm and 3.1 mm, respectively) (Table 4).

There was no significant GLD difference between sheltered and unsheltered cherrybark oak seedlings (1.3 mm and 1.4 mm, respectively), which indicates that the benefit of tree shelters may not offset the cost of installation. McCreary and Tecklin (2001) found that blue oak (*Q. douglasii*) seedlings with shelters exhibited significantly greater growth than unsheltered seedlings. However, Teclaw and Zasada (1996) found that tree shelters had no effect on growth of northern red oak.

CONCLUSIONS

Many managerial decisions can be made based upon the data collected. Survival is often linked to growing conditions, but the first step in obtaining good survival is the use of careful planting techniques and selecting species adapted to the site characteristics. If rapid height growth is desired to get oak seedlings above competing vegetation on bottomland sites, consider planting cherrybark RPM™ seedlings if economically feasible. The price of the RPM™ planting stock in 2011 was $11.50 per seedling. If the decision is left between bare-root ($0.25/seedling) and containerized ($1.25/seedling) planting stocks, this study indicated bare-root Nuttall and cherrybark seedlings outgrew the containerized seedlings in height. However, containerized planting stocks typically outgrow bare-root planting stocks due to less planting stress on the seedling (Williams and Stroupe 2002). Another consideration in deciding between species to plant is the greater GLD growth observed in Nuttall compared to cherrybark seedlings. This study also indicates that the use of tree shelters can increase height when planting bare-root Nuttall or cherrybark oak seedlings, but this alternative may not be economically feasible when labor expenses associated with installing shelters across large planting sites are considered.

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POST-HARVEST PRESCRIBED BURNING OF OAK STANDS: AN ALTERNATIVE TO THE SHELTERWOOD-BURN TECHNIQUE?

Patrick H. Brose[1]

Abstract.—Prescribed burning of two mixed-oak (*Quercus* spp.) stands in northwestern Pennsylvania 4 and 5 years after the final removal cut of a three-step shelterwood sequence was investigated. One stand was burned with hot mid-spring fire in May 2005 and the other treated likewise in May 2006. Understory inventories 3 years later showed reductions in black birch (*Betula lenta*) and red maple (*Acer rubrum*) seedlings and sprouts by 90 and 50 percent, respectively. Conversely, northern red oak (*Q. rubra*) reproduction was largely unchanged, as was that of black cherry (*Prunus serotina*). These stands now appear headed towards becoming northern red oak and black cherry stands instead of being dominated by black birch and red maple.

INTRODUCTION

In the past 10 to 15 years, many managers of oak (*Quercus* spp.) forests throughout the eastern United States have begun incorporating prescribed fire into their management plans and activities (Dickinson 2006, Hutchinson 2009, Yaussy 2000). Generally, these prescribed fires are one of two types: site preparation (restoration) burns or oak release burns (Brose et al. 2006, 2008). In the former, fire is used in mature oak stands to reduce understory shade, prepare a seed bed for future acorn crops, and stimulate the herbaceous plant community. The latter uses fire in the stand-initiation stage to free existing oak reproduction from that of taller, faster-growing hardwoods such as black birch (*Betula lenta*), red maple (*Acer rubrum*), and yellow-poplar (*Liriodendron tulipifera*). To date, almost all research and operational use of release burning have focused on fires during a shelterwood sequence, an approach commonly called the shelterwood-burn technique (Brose et al. 1999a, b), although fires conducted after the final removal harvest may also meet the competition control objective.

When applied correctly, the shelterwood-burn technique provides excellent control of competing hardwoods (Brose 2010, Brose and Van Lear 1998, Brose et al. 1999a). However, it does have a downside. Because the burning occurs during a shelterwood sequence, there is the possibility of damaging or killing some of the remaining overstory trees that are being saved for the final harvest. Fire has a well-deserved reputation for damaging and killing mature hardwood trees (Berry and Beaton 1972, Brose and Van Lear 1999, Franklin et al. 2003, Hutchinson et al. 2005, Loomis 1973, Paulsell 1957, Regelbrugge and Smith 1994, Yaussy and Waldrop 2010). Of these papers, Brose and Van Lear (1999) specifically addressed burning during a shelterwood sequence and reported a 20-percent mortality rate following spring fires. They attributed this mortality to logging slash at the base of the fire-killed residual trees and recommended preburn slash control to minimize fire damage. Additionally, unscorched residual trees after a prescribed fire can be perceived as a risky purchase by log buyers, causing reduced revenues to the landowner.

Another approach to avoiding fire damage to the residual trees is to harvest them before conducting the prescribed burn. In other words, complete all the shelterwood harvests; then burn the stand (a

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post-harvest burn). This approach would mimic the sequence of timber cutting and fire of the early 20th century that created many of our current oak stands, yet it has had little research to document the responses of the oak reproduction and the many competing hardwood species.

Two studies report the results of wildfire in young hardwood stands. Carvell and Maxey (1969) investigated the effects of a fall wildfire in a 14-year-old sapling stand in West Virginia. They found a decrease in the density of basswood (*Tilia americana*), cucumbertree (*Magnolia acuminata*), and yellow-poplar stems relative to an adjacent unburned sapling stand whereas oaks and hickories increased in number. Ward and Stephens (1989) found the effects of a wildfire in a 32-year-old stand in Connecticut to still be evident 55 years later as decreased abundance of black birch and increased amounts of oak relative to an adjacent unburned area. Additionally, two studies report the results of prescribed fires in young hardwood stands. In Alabama, McGee (1979) found that fall and spring prescribed fires in 4-, 5-, or 6-year-old clearcuts increased red maple stems and had negligible impact on the oak reproduction. Ward and Brose (2004) reported that spring burning of young sapling stands in Connecticut resulted in differential mortality rates among the principal hardwood species: 7 to 18 percent for oak, 9 to 45 percent for red maple, and 75 to 79 percent for black birch, depending on fire intensity.

In 2005 and 2006, the opportunity arose to add to this small set of fire papers by studying the effects of a single spring prescribed fire conducted 4 and 5 years after the final harvest of a three-cut shelterwood sequence. Specific research objectives were (1) to document the declines in density of the various hardwood species to the fires and (2) to document the fuel loadings and fire behavior in these young stands.

STUDY AREA

This study was conducted from 2005 to 2009 in the Allegheny High Plateau Region of northwestern Pennsylvania (Schultz 1999). This part of Pennsylvania is a dissected plateau characterized by broad, flat hills with deep valleys and steep slopes. Plateau-top elevations range from 1,700 to 2,000 feet above sea level; valley bottoms are 1,000 to 1,300 feet above sea level. Climate is classified as humid continental with warm, moist summers and cold, snowy winters. Average annual temperature is 48 °F with an average minimum mean of 17 °F in January and an average maximum mean of 82 °F in July (Cerutti 1985). Annual precipitation averages 43 inches of rain and 74 inches of snow distributed evenly throughout the year. The growing season averages 140 days. The region is extensively forested with a mix of oak and northern hardwood tree species.

The specific study site was a recently regenerated 43-acre northern red oak stand on State Game Land 29, a property of the Pennsylvania Game Commission. The stand is situated on a broad, flat hilltop so slope is almost zero and aspect is inconsequential. Soil is a Cookport silt loam (Aquic Fragiudults) formed in place from sandstone, siltstone, and shale parent material (Cerutti 1985). The site was never glaciated but is underlain with a fragipan that restricts water drainage and rooting depth. Site $index_{50}$ for northern red oak is estimated at 76 feet.

The parent stand of the study stand originated in the early 1900s when the entire region was logged and burned within a span of three to four decades (Marquis 1975). It was unmanaged until the early 1990s, when gypsy moth (*Lymantria dispar*) defoliated the stand, causing scattered mortality and some salvage harvesting. These two disturbances essentially served as a shelterwood preparatory cut as stand stocking was slightly reduced by removing some of the low-vigor trees. The cutting also coincided with an acorn crop, resulting in the abundant establishment of oak and other hardwood reproduction. In 1996, a shelterwood release cut occurred that removed approximately half the overstory trees. Shortly thereafter, the stand was divided into two sections, a 13-acre eastern block (EastBlock) and a 30-acre western block (WestBlock), and both sections were surrounded by 8-foot-high woven wire fencing to exclude white-tail deer (*Odocoileus virginiana*) from the new reproduction. The remaining overstory was harvested from both blocks in 2000.

After the final harvest, the abundant hardwood reproduction (20,000 to 30,000 stems per acre, of which 10 percent was oak) grew rapidly. By 2004, birch, cherry, and maple seedlings were overtopping the oak reproduction by several feet. The differences in abundance and size between the oaks and other hardwoods concerned the Game Commission foresters because only 125 to 150 oaks per acre could be expected to become codominant trees by age 20 in the new stand on a site of this quality (Loftis 1990). Anticipated oak mortality after age 20 would further reduce the oak component (Ward and Stevens 1994), resulting in a mixed-hardwood forest with few oaks in the main canopy. Therefore, the foresters decided to try prescribed fire to enhance the competitive position of the oaks in the regeneration pool.

METHODS

For Objective 1, fifty 0.0025-acre (1/400-acre) regeneration sampling plots were systematically located to uniformly cover both blocks (20 in EastBlock and 30 in WestBlock) and permanently marked. In each plot, all hardwood stems >1 foot tall were identified to species and tallied by height class: 1 - 3 feet (oak only), 3 - 5 feet, 5 - 10 feet, 10 - 15 feet, and >15 feet. The EastBlock plots were established in early spring 2005 and the WestBlock plots were established in early spring 2006.

For Objective 2, nine 30 feet by 30 feet fire behavior plots were established in the two blocks (three in EastBlock and six in WestBlock) in areas visually judged to have uniform fuel conditions representative of the entire block. A thermocouple was positioned in the corner and center of each plot to measure fire temperatures 1 foot above the ground at 1-second intervals. Each thermocouple was attached to a datalogger buried in the soil. Woody fuels near each thermocouple were inventoried by size class by using three 15-foot transects and the planar transect method (Brown 1974). Size classes were <0.25 inch, 0.25 - 1.0 inch, 1.0 - 3.0 inches, and >3.0 inches for 1-hour, 10-hour, 100-hour, and 1,000-hour fuels, respectively. Fuel loading in tons per acre was calculated by using equations in Brown (1974). Leaf litter and dead herbaceous fuels were collected from the end of each third transect by using a 14 inch by14 inch square and oven-dried to a constant mass to determine fuel loading in tons per acre.

The prescribed fires were conducted on May 9, 2005 (EastBlock) and May 3, 2006 (WestBlock) by Pennsylvania Game Commission personnel in accordance with agency policy and state law. At the time of each burn, the oak reproduction was still dormant as the buds were still firm or slightly swollen. However, the leaves of the non-oak reproduction (birch, cherry, maple) ranged from dormant to fully expanded with considerable variation among and within the species. Before each fire, fuel moisture was measured by using a hand-held wood moisture probe and weather conditions were monitored every 15 minutes during the burns with a belt weather kit. EastBlock was ignited as a single unit by using drip torches and a ring-fire pattern. WestBlock was divided into six subunits of approximately 5 acres, each of which was lit by using drip torches and a ring-fire pattern. When possible, the flaming front was photographed as it passed through or near each plot.

Data collection occurred at two distinct times after each burn. The dataloggers and thermocouples were collected the day after the fires. These data were used to determine the overall average maximum temperature in degrees Fahrenheit of each fire and rate-of-spread (ROS) in feet per minute. Rate-of-spread was calculated by dividing the distance between two thermocouples by the time difference between their respective maximum temperatures. Flame length (FL) was estimated to the nearest foot in each plot from the photographs by comparing the flaming front to saplings of a known height or the diameter of an occasional residual tree. The regeneration sampling plots were re-inventoried after the third growing season (early spring 2008 for EastBlock and early spring 2009 for WestBlock). Inventory procedures were identical to the preburn inventories.

For the statistical analysis, I condensed the regeneration data into six groups (black birch, black cherry, mixed-oak, pin cherry [*Prunus pensylvanica*], red maple, and miscellaneous species). The birch, two cherry, and maple groups were single species. Mixed-oak was almost entirely northern red oak, with a few black oak (*Q. velutina*) and white oak (*Q. alba*). Miscellaneous species was heavily dominated by serviceberry (*Amelanchier arborea*) but also included an occasional American beech (*Fagus grandifolia*), cucumbertree, and sassafras (*Sassafras albidum*). Mean height for each species group was estimated by multiplying the midpoint (2.0, 4.0, 7.5, 12.5, and 17.5 feet) of each height class by the number of stems in that height class, summing these results, then dividing by the total number of stems of that species group. I used paired T-tests with unequal variances (Zar 1999) to test for differences between the preburn and postburn densities and heights of these species groups in each burn unit. For all tests, $\alpha = 0.05$.

RESULTS

The two burn units were quite similar in their fuel loadings and despite being a year apart, the two prescribed fires behaved comparably to one another (Table 1). EastBlock averaged 31.4 tons per acre of fuels with nearly half in the largest fuel size class (1,000-hour). The Game Commission burned EastBlock in the early afternoon, when weather conditions were warm, dry, and sunny, with a light southwest breeze. Observed FLs were estimated between 2 and 4 feet with occasional flare-ups producing FLs of 5 to 10 feet, and ROS was measured at 3 to 5 feet per minute. The mean maximum temperature measured by the thermocouples was 969 °F with a range of 543 to 1,475 °F. WestBlock averaged slightly more fuel, 40.0 tons per acre, with half being in the 1,000-hour size class. Weather conditions during the burn were slightly warmer and drier than the EastBlock conditions. Fire behavior in WestBlock was slightly more active than in EastBlock with FLs of 5 to 12 feet, ROS of 4 to 9 feet per minute, mean maximum temperature of 1,223 °F, and a maximum temperature range of 810 to 1,667 °F. Both burns were completed without incident.

Before the fire, EastBlock averaged 15,317 stems per acre (Fig. 1). Red maple was the most abundant species at 3,938 stems per acre followed by pin cherry (3,110), mixed-oak (2,975), black birch (2,411), black cherry (1,644), and miscellaneous species (1,239). Stocking, the proportion of plots with at least one stem, for all these groups exceeded 80 percent, signifying that the regeneration

Table 1.—Fuel and weather conditions and behavior of two post-harvest prescribed fires conducted in northwestern Pennsylvania

Conditions	EastBlock	WestBlock
Date	May 9, 2005	May 3, 2006
Time of burn	12:00 to 13:30	10:00 to 15:00
Size (acres)	13	30
Total fuels (tons/acre)	31.4	40.0
Leaf litter	3.0	3.2
1-hour woody†	2.3	3.3
10-hour woody†	4.4	3.9
100-hour woody†	7.8	9.6
1,000-hour woody†	13.9	20.0
Litter cover (%)	90	100
Fuel height (ft)	2.5	3.3
Fuel moisture (%) ‡	12	10
Air temperature (°F)	72 to 75	76 to 80
Relative humidity (%)	28 to 33	22 to 25
Wind direction	Southwest	Northwest
Wind speed (mi/hr)	1 to 3	1 to 3
Cloud cover (%)	0	0
Days since rain, amt.	3, 0.1 inch	6, 0.25 inch
Flame length (ft)	2 to 4	5 to 12
Rate-of-spread (ft/min)	3 to 5	4 to 9
Mean thermocouple temp. (°F)	969	1,223
Thermocouple temp. range (°F)	543 to 1,475	810 to 1,667

† Woody fuel size classes follow Fosberg (1970).

‡ Moisture of 10-hour woody fuels.

was well distributed throughout the burn unit. Pin cherry and black birch were the tallest species, averaging 10.0 and 9.7 feet, respectively, while mixed-oak was the shortest at 1.8 feet (Fig. 2). Black cherry, red maple, and the miscellaneous species were intermediate in height with averages ranging from 4.5 to 8.2 feet.

Three years after the fire, species composition in EastBlock had changed substantially (Fig. 1). Stem density decreased by a third to 10,309 stems per acre. Oak was the most common species at 2,907 stems per acre followed closely by pin cherry (2,734). Both densities were similar to preburn values. Red maple, black cherry, and miscellaneous species were intermediate in abundance with 1,906, 1,521, and 1,001 stems per acre respectively. Of these three, only red maple had decreased from preburn levels ($p < 0.01$). Black birch was the least common postburn species, with 240 stems per acre, and had significantly decreased from preburn values ($p < 0.001$). Generally, stocking rates for all groups remained unchanged except for black birch. It was found on only 25 percent of the plots, down from 80 percent before the burn. Heights of the hardwood stems were less varied after the fires (Fig. 2). Pin cherry was the tallest at 11.3 feet, whereas red maple was the shortest at 4.4 feet, a significant decrease ($p < 0.01$) from its preburn height. Birch, black cherry, mixed-oak, and the miscellaneous species were intermediate in height with means ranging from 6.8 to 8 feet. Of these, only the mixed-oak height (7.6 feet) was significantly different ($p < 0.01$) from its preburn height (1.8 feet).

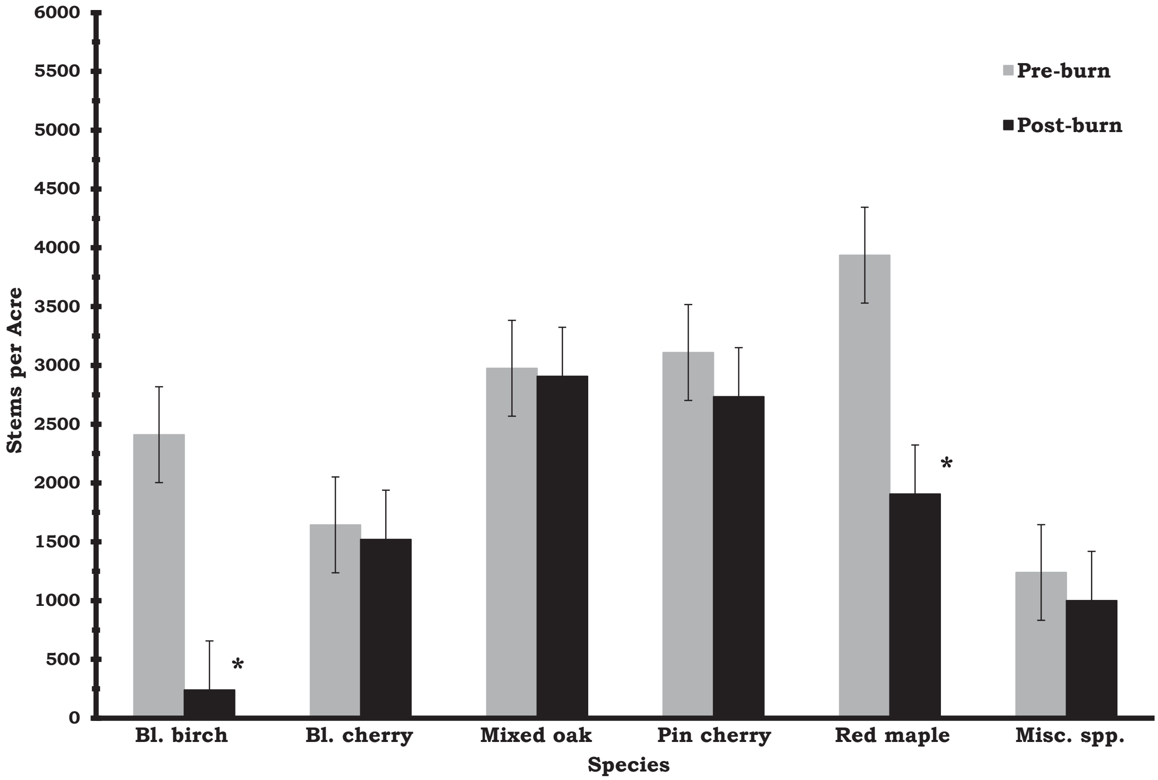

Figure 1.—Preburn and third-year postburn densities (stems per acre) of hardwood reproduction in the EastBlock unit on State Game Lands 29 in northwestern Pennsylvania. Asterisks denote postburn densities that are significantly different ($p < 0.01$) from their corresponding preburn densities.

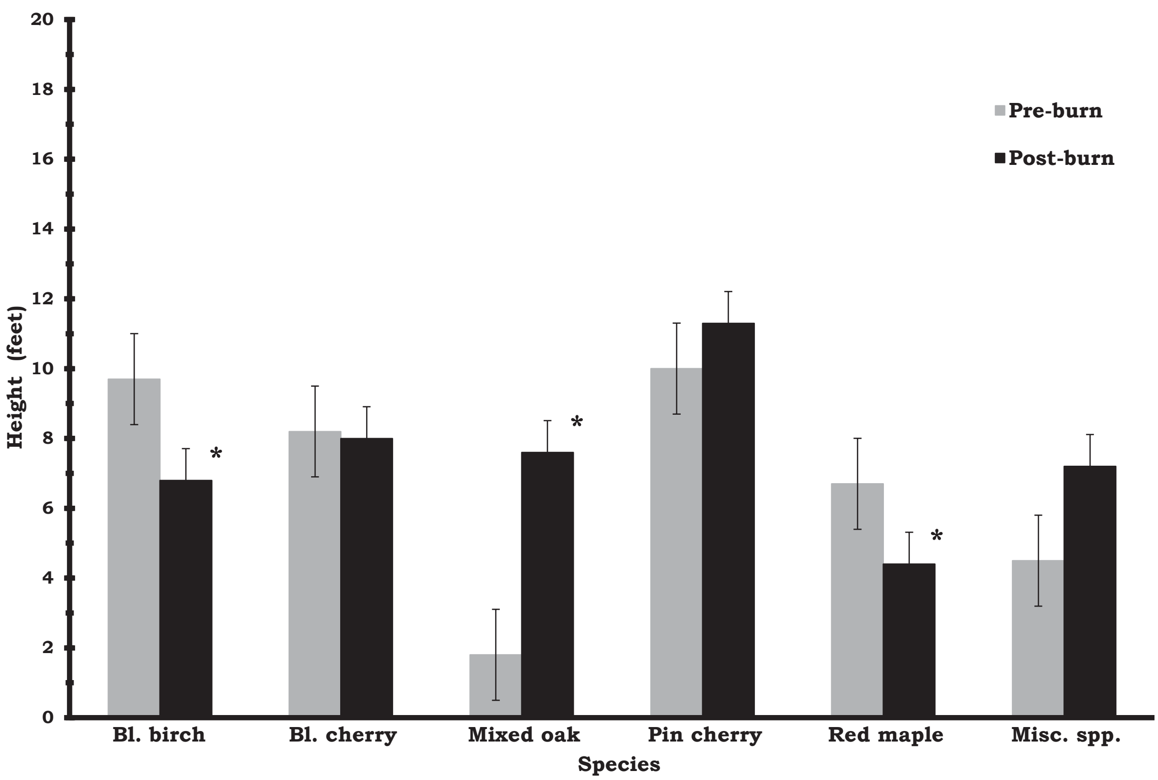

Figure 2.—Preburn and third-year postburn stem heights (feet) of hardwood reproduction in the EastBlock unit on State Game Lands 29 in northwestern Pennsylvania. Asterisks denote postburn heights that are significantly different ($p < 0.01$) from their corresponding preburn heights.

Preburn regeneration densities in WestBlock were quite similar to those of EastBlock (Figs. 3 and 4). Total regeneration density was 14,941 stems per acre, more than half of which was pin cherry (4,569) and red maple (4,054). Densities for the other species were comparable to those of EastBlock, except for black cherry, which averaged 518 stems per acre. Generally, stocking for all species exceeded 80 percent, except for black cherry, which was found on 30 percent of the plots. Pin cherry was the tallest species with a mean height of 16.5 feet, followed by black birch (13.0 feet). Black cherry, red maple, and the miscellaneous species were medium in height with means ranging from 8.0 to 10.4 feet. Oak was the shortest at 2.4 feet.

The response of WestBlock regeneration to the prescribed fire was similar to that of EastBlock regeneration a year earlier (Figs. 3 and 4). Three years after the fire, total regeneration density was 9,580 stems per acre. Pin cherry was the most abundant species (3,792), followed by mixed-oak (2,522), red maple (1,771), miscellaneous species (982), black cherry (347), and black birch (166). Of these postburn means, only black birch and red maple differed from their preburn means ($p < 0.001$ for both). Third-year postburn heights in WestBlock displayed the same interspecific distribution as those in EastBlock. Pin cherry was the tallest at 13.5 feet and red maple was the shortest at 3.5 feet. The other four species groups were intermediate in height, ranging from 5.5 to 7.7 feet. Comparing postburn heights to the corresponding preburn heights showed that black birch and red maple were significantly shorter and oak was significantly taller ($p < 0.01$ for all three). Stocking was largely unchanged except for black birch, which was found on only 27 percent of the plots 3 years after the burns.

DISCUSSION

One drawback to the shelterwood-burn technique is that the hot spring fire can cause considerable damage and mortality to the remaining overstory trees. One approach to mitigate this problem is proper slash management, which prevents fuel from accumulating at the base of valued overstory trees or removes such fuel before the fire. Another approach is to complete all harvests before burning. However, this post-harvest burning method is largely theoretical as there is little published information on fire effects in recently regenerated stands. One exception to this knowledge gap is the study by Ward and Brose (2004) that found spring fires burned readily in young hardwood stands and provided good control of black birch with little negative impact on oak reproduction. This case study helps narrow this knowledge gap by validating the findings of Ward and Brose (2004) while providing additional insights into how the reproduction of different hardwood species responds to hot spring fires.

In this study, only a few oaks, less than 5 percent, failed to sprout after the fires, even though both fires burned with high intensity. Growth of these sprouting oaks averaged 2 to 2.5 feet per year over the next 3 growing seasons with numerous stems totaling 10 to 12 feet at the time of data collection. This high survival rate and rapid height growth are explained, in part, by some of oak's silvical characteristics (Brose and Van Lear 2004) and their interaction with the timing of the treatments. Acorns have hypogeal germination, resulting in the root collars and accompanying dormant buds being located below ground where they are protected from fire. In addition, oak seedlings emphasize root development. In this study, the young oaks had 8 or 9 years of partial to full sunlight and protection from deer to develop large root systems. The fires occurred just as the oaks were breaking dormancy so their root carbohydrate reserves were at or near their maximum.

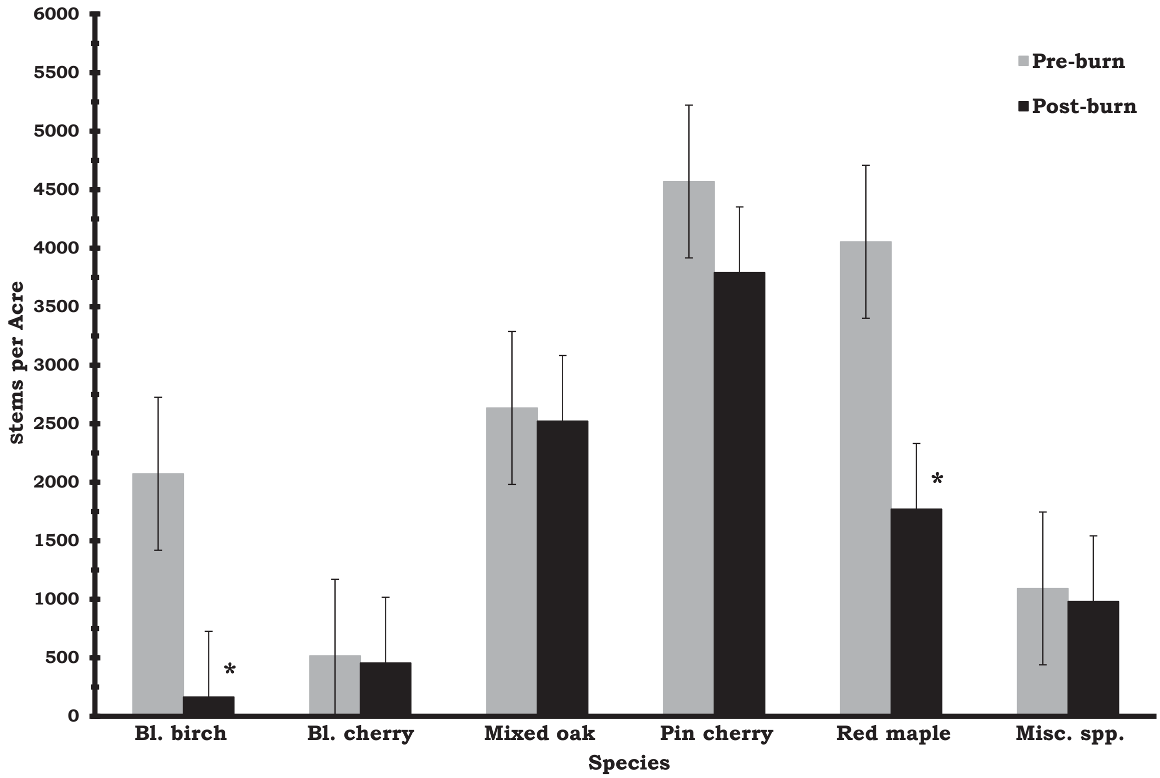

Figure 3.—Preburn and third-year postburn densities (stems per acre) of hardwood reproduction in the WestBlock unit on State Game Lands 29 in northwestern Pennsylvania. Asterisks denote postburn densities that are significantly different ($p < 0.01$) from their corresponding preburn densities.

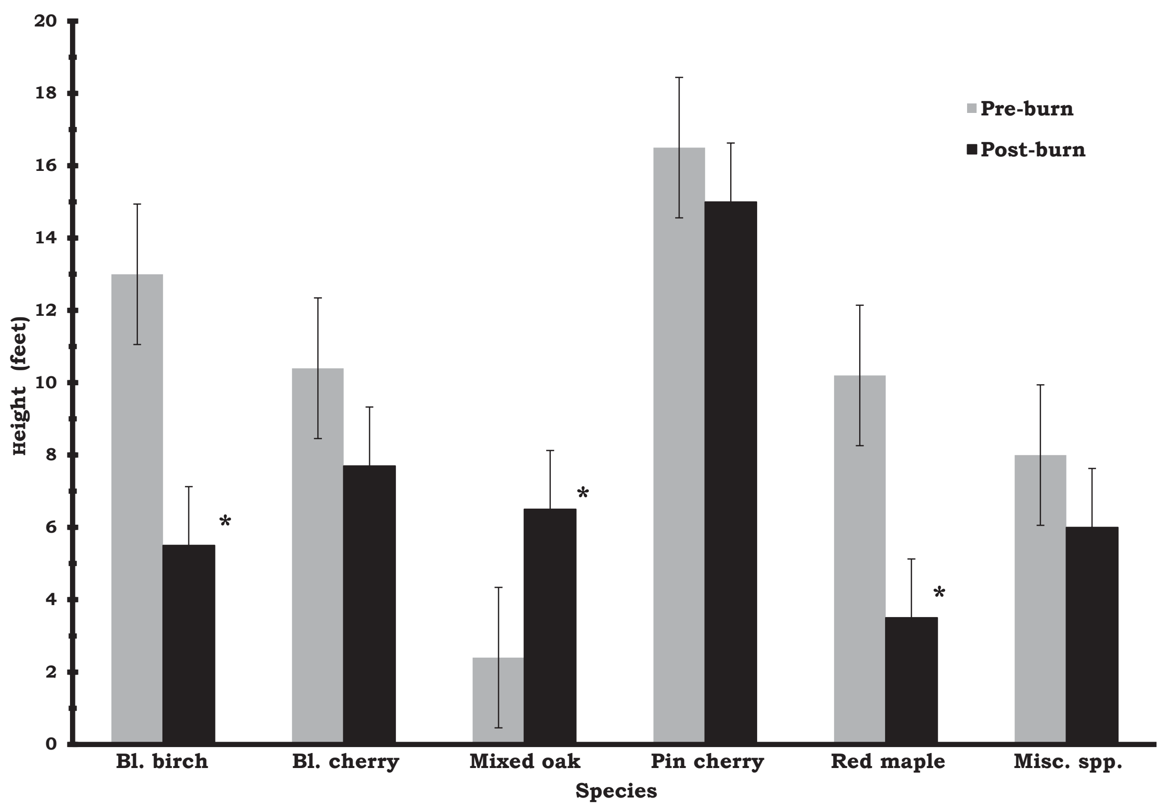

Figure 4.—Preburn and third-year postburn stem heights (feet) of hardwood reproduction in the WestBlock unit on State Game Lands 29 in northwestern Pennsylvania. Asterisks denote postburn heights that are significantly different ($p < 0.01$) from their corresponding preburn heights.

Conversely, more than 90 percent of the black birches failed to sprout postfire. This high mortality for birch confirms the finding of Ward and Brose (2004), when they reported a 76-percent mortality rate for black birch after a hot spring fire in Connecticut. Black birch has small, shallow roots and virtually all stems had already fully leafed out when the fires in the current study occurred. Consequently, they were highly susceptible to fire at that time. The birch that did survive and sprout were confined to small areas that did not experience high fire intensity. However, those survivors were growing just as fast as most of the other species so they will be formidable competitors in parts of these burn units for years to come (Heggenstaller 2010).

Only about half the red maple sprouted postfire, which is consistent with the 45-percent mortality rate reported by Ward and Brose (2004) after one burn. Like black birch, red maple has a small, shallow root system. However, at the times of the burns, red maple stems were in various stages of leaf expansion. Some were still dormant or with swollen buds, but many had leaves that were 25 to 50 percent expanded and there were a few with nearly fully expanded leaves. This wide variety of leaf expansion coupled with variations in fire intensity probably accounts for the 50-percent mortality rate. Red maple height growth was substantially slower after the fires relative to the other species. This result can be attributed to the degree of leaf expansion, the subsequent weather (the summers following the fires were dry), and the abundance of pin cherry, a species known for capturing much of the soil nitrogen following a disturbance. Red maple will likely not become a dominant species in these stands as they mature over the coming decades (Heggenstaller 2010).

The black cherry, pin cherry, and serviceberry (the dominant species of the miscellaneous group) responded to the fires in a manner comparable to the oaks. Stem densities declined from 10 to 15 percent across both fires for these three species. Pin cherry, also known as fire cherry, can sprout from the roots in addition to the root collar. Therefore, even though the fire killed virtually all the stems, most were simply replaced by a root sucker. Additionally, pin cherry seed in the forest floor likely germinated and contributed new seedlings that reduced the overall density decline. Postburn height growth was rapid for pin cherry with most stems nearly regaining their preburn heights within 3 years.

The low density decline and relatively rapid height growth of black cherry and serviceberry were somewhat of a surprise as there is no literature on their responses to fire. The finding of a low mortality rate for both is good because black cherry is the premier timber species of northwestern Pennsylvania and both species provide soft mast to a wide variety of wildlife.

Preburn densities of black cherry differed widely between EastBlock and WestBlock (1,644 and 518 stems per acre) likely because WestBlock had nearly 50 percent more pin cherry than EastBlock. In full sunlight, pin cherry outcompetes black cherry, causing the latter to have lower stem densities and reduced height growth (Ristau and Horsley 1999).

Before the fires, Game Commission personnel expressed concerns about the fuel loadings and expected fire behavior. One concern was that the lack of leaf litter (~3 tons per acre) would make conducting the burn difficult, requiring frequent ignitions and causing a patchy burn. The other was that the heavy loading of large fuels (22 to 30 tons per acre) would cause extreme fire behavior and lead to spot fires outside of the control lines. Neither concern became a problem. Fire easily carried through both units so the paucity of leaf litter was not an obstacle to a complete burn. The large fuels did cause long flame lengths, upwards of 20 feet in some cases, but spotting was minimal due to light winds and good smoke dispersal. Recently regenerated oak stands can be burned easily, safely, and without incident by practicing sound principles of prescribed fire planning and implementation.

These burns were a management success. Before the burns, only about 5 percent, or 125 to 150 stems per acre, of the northern red oak seedlings could be expected to survive and become codominant by age 20 (Loftis 1990). Additional oak mortality during the ensuing decades would further reduce these numbers and eventually result in a mixed hardwood forest containing few oaks in the main canopy (Ward and Stephens 1994). The fires changed these dominance probabilities in favor of oak. The suppressed oak reproduction was freed from the larger competition, and the undesirable black birch and red maple regeneration was markedly reduced from preburn levels. As of 2011, the oaks are still of equal height with all other species except pin cherry, which is the tallest. Now Loftis' (1990) dominance probability model predicts more than 400 codominant oak saplings at age 20, and stand development beyond that point will culminate in an oak-dominated stand like the one harvested in the 1990s.

The abundance of pin cherry is a concern as this species can dominate a site during early stand development to the detriment or exclusion of most other species (Ristau and Horsley 1999). But crop tree management can be used to maintain oak in a competitive canopy position (Brose et al. 2008, Miller 2000, Miller et al. 2007).

Although these results are encouraging, post-harvest burning needs more research before it can be fully endorsed as a management technique. A long-term study at several locations comparing the post-harvest burning to the shelterwood-burn technique and clearcut/shelterwood prescriptions without fire would be beneficial in this regard. Furthermore, post-harvest burning has the same biological constraints as the shelterwood-burn technique in regards to the existence of sufficient numbers of oak seedlings <u>before</u> beginning the regeneration process and the same operational constraints of prescribed burning. However, based on the results reported in this paper, post-harvest burning appears to be a viable alternative to the shelterwood-burn technique when there is concern about fire damage and mortality to high-value overstory trees.

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RESPONSE OF NATURALLY REGENERATED AND UNDERPLANTED WHITE OAK (*QUERCUS ALBA* L.) SEEDLINGS 6 YEARS FOLLOWING MIDSTORY REMOVAL

Jared M. Craig, John M. Lhotka, and Jeffrey W. Stringer[1]

Abstract.—Historically, the abundance of red maple and shade-tolerant understory species was limited by fire and other disturbances. In the absence of periodic disturbance, regeneration of oaks with intermediate shade tolerance has been hindered due to inadequate light conditions created by shade-tolerant midstory trees. Research suggests that midstory removal in oak-dominated forests can create light conditions that enhance the growth of oak advance reproduction. The purpose of this study is to compare the competitive ability of underplanted versus naturally regenerated white oak seedlings under a midstory removal. In 2005, a 0.2-ha midstory removal and control were established at study sites. Seedling heights and basal diameters were measured at treatment establishment and after six growing seasons. Results showed seedling growth was higher under the midstory removal, and height growth of underplanted seedlings was greater than that of advance regeneration. It was also found that diameter growth was greater under the midstory removal; however, there was no difference between seedling types. Findings from this study provide further insight about the dynamics of oak response under a midstory removal and suggest regeneration methods for improving the competitive ability of white oak.

INTRODUCTION

Oak-dominated forests throughout the United States rely on periodic disturbances to regenerate successfully. One historic disturbance was fire. After the arrival of European settlers in the United States, fire was suppressed in most areas (Abrams 2003). Without regular disturbances, shade-tolerant species such as red maple (*Acer rubrum* L.), sugar maple (*A. saccharum* Marsh.), and American beech (*Fagus grandifolia* Ehrh.) became more prevalent (Abrams 1998, 2003). As shade-tolerant trees increase in number, they are able to form dense midstories that inhibit the growth of oaks with intermediate shade tolerance.

One of the challenges for successful oak regeneration is increasing light to favor oaks over shade-tolerant species while also limiting the light to shade-intolerant species such as yellow-poplar (*Liriodendron tulipifera* L.). In various studies conducted in forests dominated by white oak (*Quercus alba* L.), northern red oak (*Q. rubra* L.), and cherrybark oak (*Q. pagoda* Raf.), light levels in unaltered stands have been found to be 2 to 8 percent of full sunlight (Dillaway and Stringer 2006, Gottschalk 1994, Lhotka and Loewenstein 2009) and as low as 1 percent (Dey and Parker 1996). Several studies have suggested that 20 to 30 percent is the optimal light range for developing competitive oak seedlings (Dillaway and Stringer 2006, Gottschalk 1994, Guo et al. 2001, Jarvis 1964, Phares 1971).

The number of oak seedlings present at the time of release is also a major factor in the future success of a stand. Depending on stand condition, it has been suggested that 250 to 1,000 seedlings per ha should be present (Johnson and Jacobs 1981, Sander 1979, Spetich et al. 2004). Sander (1972)

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Table 1.—Absolute and relative density and basal area across all sites before and after midstory removal treatments

Species	Before treatment				After treatment			
	Trees* ha^{-1}	Relative abundance (%)	Basal area (m^2 ha^{-1})	Relative basal area (%)	Trees ha^{-1}	Relative abundance (%)	Basal area (m^2 ha^{-1})	Relative basal area (%)
White oak	109	5.5	21.5	27.4	92	30.6	20.7	32.8
Other oaks	61	3.1	18.2	23.2	54	18.1	18.0	28.7
Maples	1,138	57.5	14.8	18.9	49	16.4	5.9	9.4
American beech	308	15.6	4.8	6.1	8	2.7	3.7	5.9
Hickories	125	6.3	12.8	16.4	68	22.4	10.7	17.0
Black gum	69	3.5	1.9	2.5	13	4.4	1.6	2.6
Ash	38	1.9	1.7	2.2	7	2.2	1.1	1.7
Yellow-poplar	18	0.9	0.8	1.1	3	1.1	0.3	0.4
Other hardwoods	115	5.8	1.8	2.3	7	2.2	0.9	1.5
Total	1,981	100.0	78.3	100.0	301	100.0	62.9	100.0

*Greater than 2.5 cm diameter at breast height (d.b.h.)

also found that seedlings greater than 137 cm were likely in a better position to be recruited to the overstory after release. When forests are not able to attain adequate advance reproduction, underplanted seedlings can be utilized to increase oak abundance (Dey and Parker 1997b, Gardiner and Yeiser 2006, Johnson et al. 1986).

A replicated midstory removal study was established in 2005 to investigate what effect increased light would have on the height and diameter growth of white oak seedlings. The study is of particular interest because limited information is available on how the growth of white oaks is affected when understory light levels are enhanced using midstory removal. This paper reports on the effect of the midstory removal treatment on underplanted and naturally regenerated seedlings following six growing seasons.

STUDY AREAS

Three experimental sites (Water Plant, Pigg House, and Fentress Spur) were established in January 2005 in Berea College Forest. The forest is located in Madison County, Kentucky, which is on the western edge of the northern Cumberland Plateau physiographic region. Each site was dominated by Weikert channery silt loam, a well-drained soil common to the region. At the time of treatment implementation, basal areas of the site ranged from 24.5 to 27.9 m^2 ha^{-1}, and canopies were dominated by white oak, black oak (*Q. velutina* Lam.), chestnut oak (*Q. prinus* L.), and hickories (*Carya* spp. Nutt.). The understory was primarily composed of red maple, sugar maple, and American beech. Relative abundance and initial basal areas of major species before and after the treatment are presented in Table 1.

An analysis of site quality found the mean canopy height to be 27.9 m, and plots had an average site index of 19.5 m at age 50. Complete management data are unavailable, but tree cores taken from the sites suggest that there has been no major disturbance for 100 years.

METHODS

At each site, two areas with similar slope and aspect were chosen. One of these areas was randomly assigned a midstory removal treatment; the other was designated as the control. The midstory removal experimental unit consists of a 0.2-ha square surrounded by a 9.5-m buffer to minimize edge effects. In these areas, 20 percent of initial basal area was removed by chainsaw felling all trees greater than 2.5 cm in diameter at breast height (d.b.h.) and working upward until the target basal area was reached. No dominant or codominant trees were removed in this step. Felled trees were cut into small sections and stacked within the plots to decompose. Small stems and slash were carried outside of plot boundaries. During treatment, cut stumps were sprayed with 100 percent Roundup Pro® (Monsanto Company, St. Louis, MO) to prevent resprouting. The control experimental unit was created by delineating another 0.2-ha square plot in the predetermined area while leaving the midstory intact.

After treatments were established, each experimental unit was divided into 36 squares measuring approximately 7.6 m on each side. Six of these squares were randomly selected to be planted with twelve 1-0 bare-root white oak seedlings. Planting occurred in March 2005. Six more squares were also randomly selected as natural regeneration cells in which every white oak seedling present was measured. The remaining cells were part of another study and not pertinent to this paper. Each individual treatment plot ultimately received 72 underplanted seedlings, resulting in a total of 432 seedlings planted over all plots. There were 174 advance regeneration white oak seedlings over the three control sites and 178 seedlings in the removed treatments for a total sample size of 352 natural white oaks.

Initial measurements for all seedlings were taken before the 2005 growing season. These measurements consisted of total height as well as ground line diameter. In 2010, after six growing seasons, seedling heights and diameters were remeasured. Seedling height was determined by using a meter stick held vertically at the base of the plant and recording the height of the terminal leader. Diameter was recorded using digital calipers. Two perpendicular readings were taken to the nearest 0.1 millimeter at the intersection of the stem and soil. Final seedling diameter was the average of the two perpendicular readings. It should also be noted that when final measurements were taken, there was little to no evidence of damage from deer browsing or other damaging agents.

Growth data were analyzed as a randomized complete block analysis of variance (ANOVA) to test whether height and diameter growth after six growing seasons was significantly different between midstory removal treatments and seedling type (i.e., natural regeneration versus underplanted). The ANOVA model used mean height and diameter growth by experimental unit (i.e., 0.2-ha treatment plot) to avoid pseudoreplication. Site was used as the blocking factor in the ANOVA. The interaction between midstory removal treatment and seedling type was also tested for significance, but was found to have no effect. Percentage of seedling survival after six growing seasons was analyzed using logistic regression to test whether there were differences between treatments and seedling type. All data conformed to assumptions of normality and homogeneity of variance. Significance for tests was set at a value of $\alpha = 0.05$.

Table 2.—Average heights and basal diameters (± SE) of white oak seedlings before and after treatment

	2005		2010	
Dependent variable	Natural regeneration	Underplanted	Natural regeneration	Underplanted
Height (cm)				
Control	9.9 ± 0.42	10.9 ± 0.42	25.5 ± 2.3	40.2 ± 2.0
Removal	9.8 ± 0.43	11.1 ± 0.27	34.1 ± 4.2	53.1 ± 3.3
Diameter (mm)				
Control	2.96 ± 0.11	5.17 ± 0.10	3.10 ± 0.22	5.27 ± 0.33
Removal	3.14 ± 0.13	5.43 ± 0.14	4.56 ± 0.42	6.78 ± 0.30

RESULTS

At the time of establishment, there were no height differences between treatment ($p = 0.88$) or seedling type ($p = 0.23$). Diameters were found to be the same within individual seedling types ($p = 0.42$); however, a difference was noticed between natural versus underplanted seedlings ($p < 0.0001$). Average initial height was found to be 9.9 cm for advance reproduction white oaks and 11.0 cm for underplanted seedlings. Average diameters in 2005 were 3.05 mm and 5.30 mm for advance reproduction and underplanted seedlings, respectively (Table 2).

After six growing seasons, underplanted seedlings in the removal treatment were found to have the highest total height on average (53.1 cm), followed by underplanted white oaks in the control (40.2 cm). Advance regeneration oaks in the removal treatment had an average total height of 34.1 cm, and advance regeneration seedlings in the control had the smallest average height (25.5 cm) (Table 2).

Underplanted seedlings were found to have greater height growth versus advance reproduction seedlings ($p < 0.0001$) six growing seasons following midstory removal. Seedlings in the midstory removals were also found to have grown more, on average, than those in the controls ($p = 0.0002$). Average height growth was found to be greatest for underplanted seedlings under the midstory removal (42.0 cm). Conversely, the least growth was seen among advance reproduction seedlings in the control (15.6 cm) (Table 3).

Diameter growth was found to be significantly different between treatments ($p < 0.0001$), but not between different seedling types in the same treatment ($p = 0.5297$) (Table 3). Among advance reproduction seedlings, average diameter growth was 1.41 mm in the removed treatment versus 0.09 mm in the control. Underplanted seedling diameters in the midstory removal increased an average of 1.65 mm, whereas those in the control increased an average of only 0.10 mm over the six growing seasons.

Analysis of seedling survival found that both treatment ($p < 0.0001$) and seedling type ($p < 0.0001$) were significant predictors of seedling survival; however, there was no significant interaction between factors. Naturally regenerated seedlings had better survival than underplanted seedlings. After six growing seasons, highest overall survival was 93 percent as seen among advance reproduction in the removal treatment. The survival rate of underplanted seedlings in the removal treatment was second highest at 75 percent. A similar pattern was observed within the controls with naturally regenerated seedlings and underplanted seedlings having overall survival rates of 69 and 50 percent, respectively (Table 4).

Table 3.—Average white oak seedling height and diameter growth (± SE) after six growing seasons

Dependent variable	Natural regeneration	Underplanted
Height (cm)		
Control	15.6 ± 2.0 A*	29.2 ± 3.9C
Removal	24.3 ± 1.9 B	42.0 ± 3.4D
Diameter (mm)		
Control	0.09 ± 0.23A	0.10 ± 0.33A
Removal	1.41 ± 0.37B	1.65 ± 0.27B

*Same letters indicate no significant difference between treatments and seedling types at $\alpha = 0.05$.

Table 4.—White oak seedling survival (%) after six growing seasons

	Treatment	
Seedling type	Control	Removal
Natural regeneration	69 A*	93 B
Underplanted	50 C	75 A

*Same letters indicate no significant difference between treatments and seedling types at $\alpha = 0.05$.

DISCUSSION

Studies examining cherrybark oak have found significant yearly height increases of 16 cm for underplanted seedlings (Lhotka and Loewenstein 2009) and 5.5 cm for naturally regenerated seedlings (Lockhart et al. 2000) following a midstory removal. Lhotka and Loewenstein (2009) also found significant diameter growth of 1.9 mm after two growing seasons. Dey and Parker (1997b) found height growth of 13.1 cm for underplanted red oak seedlings 2 years following a shelterwood treatment. This same study also found negligible growth for seedlings planted under intact midstories. Another northern red oak study in Wisconsin found underplanted seedlings were nearly twice as tall 5 years following an understory removal when compared to seedlings in the control (Lorimer et al. 1994). In the same study, seedling height was nearly doubled for naturally grown oaks under a midstory removal.

Although this study examined white oak, results are consistent with previous findings from other species which indicate that underplanted seedlings perform better when under a midstory removal. As with Lorimer et al. (1994), underplanted seedlings exhibited increased growth compared to naturally regenerated oaks. These results suggest that, for white oak-dominated sites of the Appalachian Mountains, underplanting may be a viable option for increasing the number of vigorous seedlings prior to release.

The success of the underplanted seedlings over natural seedlings may be a result of initial stem diameter. Although heights of both seedling types were not significantly different at inception, the diameters of underplanted seedlings were larger. Dey and Parker (1997a) found initial stem diameter to be the best indicator of the success of underplanted red oak seedlings as this relates to root size and carbohydrate stores. It has been suggested that, for northern red oaks, seedling stock should be no less than 9.5 mm (Johnson et al. 1986). Initial diameters for planted oaks in this study averaged 5.2 mm, but no information is available for white oaks on the relationship between initial basal diameter and long-term success.

Diameter growth after 6 years illustrates the ability of the intact midstory to limit growth. Minimal diameter increase under a midstory was also seen by Dey and Parker (1997b). In the control treatment of our study, both underplanted and natural seedlings experienced an average yearly increase of only 0.02 mm. Significant diameter growth was seen in the removal treatment, where white oak diameters showed more than a tenfold increase. This result underscores the importance of maintaining adequate light levels during seedling development. Because initial diameters of naturally regenerated seedlings in this study were generally small, future studies should attempt to assess the response of advance regeneration white oak seedlings that have larger diameters at the time of treatment.

In terms of height growth, oaks planted in the midstory removal grew an average of 7.0 cm each year, which is similar to that seen with northern red oak (Lorimer et al. 1994). To reach the height of 137 cm as suggested by Sander (1972) for competitive seedlings at the time of final release, the oaks from this study would require 13 more growing seasons at the current growth rate. Planting more developed seedlings and increasing initial light levels may be the best approach for effectively regenerating similar stands.

One option for increasing growth rates would be to use older seedling stock such as 2-0 bare-root or containerized seedlings. These plants should have larger initial root systems that are more vigorous and could speed early growth (Dey and Parker 1997a, Jacobs et al. 2005). Increasing the initial light levels through the removal of more basal area may also speed the growth of white oak seedlings. Given the site index of the experimental units, Loftis (1990) and Spetich et al. (2004) would suggest a 40- to 60-percent reduction in initial basal area, whereas this study eliminated only 20 percent of basal area. Achieving the suggested reduction in basal area would mean potentially removing trees occupying a dominant or codominant canopy position.

Proper timing of the initial midstory removal and final release should not be overlooked (Loftis 1990). Tolerant species also respond favorably to increased understory light levels (Clinton et al. 1994), so the final harvest should be performed when enough oak seedlings have reached a competitive size, but before oak seedlings become overtopped by shade-tolerant species. Loftis (1990) suggests that the final harvest should be completed approximately 10 years following midstory removal; however, exact timing for a final release is dependent upon site conditions, species silvics, and other environmental factors.

CONCLUSIONS

Few studies have looked at the effect of a midstory removal on the growth and vigor of white oak seedlings. Results after six growing seasons show that the midstory removal significantly increased the height and diameter growth of seedlings. Greatest height and diameter growth was observed among oak seedlings planted under a midstory removal, suggesting that artificial regeneration is a worthwhile practice for increasing the number of vigorous seedlings before a final harvest. The minimal diameter growth exhibited by seedlings under an intact midstory also suggests that, for best growth in both height and diameter, forest managers should plant seedlings immediately after the midstory removal.

When underplanted seedlings are used, survival should also be considered. Although underplanted seedlings were shown to grow faster than natural seedlings, they had a lower survival rate. This result suggests that underplanted seedlings should be used along with natural regeneration to achieve necessary seedling densities.

Despite the significantly higher height and diameter growth of underplanted seedlings under the midstory removal, seedlings have not reached the recommended height for release. Additional research on whether larger bare-root or containerized seedlings can improve early growth and survival of white oak underplanted after midstory removal is warranted.

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CHANGES TO OAK WOODLAND STAND STRUCTURE AND GROUND FLORA COMPOSITION CAUSED BY THINNING AND BURNING

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Abstract.—Our objective was to quantify the cumulative effects of prescribed burning and thinning on forest stocking and species composition at a woodland restoration experiment site in the Ozark Highlands of Missouri. Our study used four treatments (burn, harvest, harvest and burn, control) on three slope position and aspect combinations (south, north, ridge) replicated in three complete blocks. Harvested stands were thinned from below to 40 percent residual stocking. Two prescribed fires were applied to both burn and harvest-burn treatment units in a 5-year period. Results reflect changes that have taken place over a 6-year period, from pretreatment conditions to 1 year after the last fire. In this period, there was a 10-percent reduction in the stocking in burned stands compared to control and a 6-percent reduction in harvested and burned stands compared to harvested stands. Compared to the control, percentage ground cover of woodland indicators was seven times greater in burned stands, six times greater in harvested stands, and 22 percent greater in harvested and burned stands. There was no significant ($P > 0.05$) interaction between aspect and treatment on stocking or ground flora cover. This study indicated that silvicultural treatments do achieve various goals that are common to managers who aim to restore woodland communities.

INTRODUCTION

Woodland communities are characterized by open midstories and understories and dense ground flora composed of forbs, grasses, sedges, and shrubs (Nelson 2005, Nuzzo 1986, Taft 2009). They once were common in the western Central Hardwoods Region and prairie-forest transition zone, where low-intensity fires occurred frequently (Guyette et al. 2002, Taft 2009). In the absence of fire, many of the oak (*Quercus* spp.) woodland ecosystems throughout much of the Midwest have succeeded to compositions and structures resembling those of mature oak forests (Johnson et al. 2009, Nowacki and Abrams 2008). In some oak ecosystems, mesophytic vegetation is replacing fire-dependent species at a rapid rate (Ladd 1991, Nowacki and Abrams 2008). Shifts in species composition and structure within woodland communities could jeopardize the biotic diversity, wildlife habitat, and ecosystem processes that occur in each environment (Peterson and Reich 2001, Shifley et al. 2006). These changes are deemed undesirable by many managers of state and private lands, many of whom have restoration objectives for their forests.

There is increasing interest in restoring the structure and composition of oak woodlands (Ladd 1991, Peterson and Reich 2001). Prescribed fire is considered an important woodland restoration tool (Nowacki and Abrams 2008, Taft 2009) largely for two reasons. Fire was the ecosystem process that maintained oak woodlands in the past, and it reduces stand density, particularly by removing fire-sensitive species in the understory and thereby increasing the sunlight reaching the

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Table 1.—Density, basal area, and stocking (Gingrich 1967) for all treatments[a]

	Trees per acre			Basal area (ft^2/acre)			Stocking (Percent)		
	2001	2003	2006	2001	2003	2006	2001	2003	2006
Burn	370.2	262.2	213.3	104.8	99.5	95.9	94.1	86.4	81.9
Control	350.6	317.5	303.5	107.3	105.6	111.5	94.7	92.1	95.9
Harvest	338.3	81.7	80.8	112.3	52.1	52.9	93.8	42.9	43.3
Harvest-Burn	370.7	55.7	52.8	105.1	37.8	40.4	94.1	31.1	32.9

[a] Data for 2001 were collected pretreatment, data for 2003 were collected after timber harvests and the first prescribed fire, and data for 2006 were collected after the second prescribed fire.

ground (Hutchinson et al. 2005, Johnson et al. 2009). Much has been written about how the use of prescribed fire modifies forest structure and favors oak regeneration, especially in mesic ecosystems, where regenerating oaks has remained an important problem (Arthur et al. 1998, Dey and Hartman 2005, Hutchinson et al. 2005). However, fewer studies have measured the effects of both fire and commercial overstory harvests (Albrecht and McCarthy 2006, Brose et al. 1999) on forest structure and ground flora composition on upland sites at a landscape scale.

The objectives of this study were to examine the effects of prescribed fire, thinning, and their interactions with slope position and aspect on forest structure and ground flora species composition. Stand structure was evaluated based on changes in the diameter distribution and overall stocking by diameter. Ground flora species composition was evaluated based on changes in the cover of forbs, legumes, graminoids, shrubs, vines, and woody seedlings in the understory.

STUDY AREA

This project was conducted in southeastern Missouri at Logan Creek Conservation Area (CA) and Clearwater Creek CA, which are managed by the Missouri Department of Conservation. When the study was initiated, the sites were fully stocked and composed primarily of oak-hickory and oak-pine forest types (Table 1). No management or documented fire had been recorded for at least 40 years. Sites were within the Black River oak-pine woodland/forest hills landtype association, characterized by steep hillslopes consisting mainly of cherty, low-base soils and occupied by second-growth forests (Nigh and Schroeder 2002).

METHODS

Study Design and Treatments

This study is designed so that four treatments are applied across three slope position and aspect combinations: north-facing slopes (aspect 315º to 45º), ridge tops (slopes <8 percent), and south-facing slopes (aspect 135º to 225º). Treatments were prescribed fire (burn), commercial thinning (harvest), their combination (harvest-burn), and control. Treatments were paired by slope and aspect to create twelve 5-acre units (hereafter “treatment units”) per block. Three complete blocks were initially established: two at Clearwater Creek CA and one at Logan Creek CA, each approximately 60 acres in area. Due to unsuitable weather conditions, however, some of the burn units in block three were not treated on schedule. Consequently block three was not included in our analyses.

Table 2.—Observed parameters for fire behavior averaged across blocks one and two

	Treatment	Rate of spread		Fireline intensity		Flame height
		Nelson[a]	Byram[b]	Nelson[a]	Byram[b]	
		---------------ft/min---------------		----------BTU/ft/sec----------		inches
1st fire	Burn	2.4	1.2	43	22	20
	Harvest-burn	3.6	1.9	76	41	24
2nd fire	Burn	Not determined	Not determined	28	14	15
	Harvest-burn	Not determined	Not determined	72	40	18

[a] Based on an equation by Nelson (1986).
[b] Based on an equation by Byram (1959).

Timber harvests occurred during summer and early fall 2002, before the first burn. Harvesting reduced stand density to 40 percent stocking (Gingrich 1967) by thinning from below. However, to achieve stocking goals, some dominant and codominant trees were removed. Preferred trees for retention were white oak (*Quercus alba* L.) and shortleaf pine (*Pinus echinata* Mill.) because of these two species' fire tolerance. Prescribed fires were applied during spring for burn and harvest-burn units in 2003 and 2005. Each burn was executed by using the ring fire method, while burning the ridges at the same time. Fire behavior parameters are included in Table 2.

Fire Behavior Measurements

Fire behavior was characterized by using passive fire behavior sampling techniques, passive flame height sensors, and rate of spread (ROS) clocks. Flame height data were collected by using passive flame height sensors, which were placed in the three overstory plots within each stand. Passive flame height was measured by using 12 strands of cotton string treated with fire-retardant, which were suspended between 2 wires, one at fuel bed height and the other approximately 7 feet above the fuel bed (Kolaks 2004). Additionally, trained observers used visual aids to determine flame-tilt angle as the fire front passed through the flame height sensors.

Estimated average and maximum flame lengths were derived by averaging flame heights, recording the tallest flame height logged by the series of sensors, and then applying the flame tilt angle. In the same plots, five ROS clocks were inserted with one at plot center and one at 50 feet in each cardinal or sub-cardinal direction (Kolaks et al. 2005). Rate of spread and direction were calculated by using at least three measurements from the buried ROS clocks or the average of all the triangle combinations, if more than three clocks activated and worked properly (Kolaks 2004, Simard et al. 1984).

Vegetation Sampling

Permanent plots were established during summer along a transect following the contour of the slope that is approximately 700 feet long. This transect contained both woody and herbaceous vegetation plots. All trees ≥1.5 inches in diameter at breast height (d.b.h.) were inventoried in three 0.33-acre circular plots randomly located along transects within each treatment unit. All trees and shrubs >3.3 feet tall and <1.5 inches d.b.h. were inventoried in fifteen 0.002-acre circular subplots randomly located along transects within each treatment unit. Trees ≤3.3 feet tall, ground flora, and vines were sampled in thirty 3.28 feet by 3.28 feet quadrats that were randomly located along transects within each treatment unit. Within each quadrat all live herbaceous plants and tree seedlings were identified to species and cover was estimated to the nearest percent. Post-treatment understory data were collected in the same plots and quadrats in summer 2003 and again in summer 2005 (i.e., during the first growing season after harvest and/or prescribed fire was applied). Data for trees and shrubs > 3.3 feet tall were collected during the dormant season following the understory data collection (i.e., winter 2003-2004 and winter 2005-2006).

Data Analysis

We used the general linear models procedure (Proc GLM, SAS version 9.1, SAS Institute, Cary, NC) to examine the effects of treatment (burn, harvest, harvest-burn, or control) and slope position and aspect (north-facing slope, ridge, south-facing slope) and the interaction between treatment and slope aspect. The error term was the block*treatment*slope aspect interaction. Response variables were the change in percentage stocking (post-treatment – pretreatment) by diameter size class for woody vegetation and the change in percentage cover of ground flora by forbs, legumes, graminoids, shrubs, vines, and woody seedlings in the understory. Post-treatment included the sampling period following the second burn. We limited our analysis to blocks one and two because they were burned two times during the study period. The vegetation data for 2003 (after one burn) were examined but not included in the analysis. To test for significant effects ($\alpha = 0.05$), we compared means by using Fisher's least significant difference test.

RESULTS

Changes in Overstory Structure

Prior to treatment, the average stocking for all stands was greater than 94 percent and sawtimber (>10.5 inches d.b.h.) accounted for the majority of stocking (Table 1). The two prescribed burns caused only minor reductions in the overall stocking (Table 3). There was a 10-percent stocking reduction in the burn treatment compared to control and only a 6-percent reduction in the harvest-burn treatment compared to the harvest treatment. Most of the reductions due to the prescribed fire were in small tree sizes (1.5 to 5.4 inches d.b.h.) and greater differences occurred between the control and the burn treatment than between the harvest and the harvest-burn treatments (Table 3). When sampled in 2006, density (trees per acre) was reduced twice as much in burn treatments as in control, and five times as much in harvest and harvest-burn treatments as in control (Fig. 1). We found no significant differences among slope position and aspect combinations or with their interactions with treatment.

Table 3.—Changes in level of percentage stocking (pre- to post-treatment)[a]

Size class (d.b.h.)	Control	Burn	Harvest	Harvest-Burn
Small trees (1.5 - 5.4 inches)	-2.4 a	-9.3 b	-11.9 bc	-17.7 c
Small poles (5.5 - 8.4 inches)	0.57 a	-4.3 b	-8.0 c	-9.0 c
Large poles (8.5 - 10.4 inches)	-0.89 a	-2.3 a	-5.7 b	-5.7 b
Saw timber (>10.5 inches)	7.2 a	6.1 a	-30.2 b	-25.6 b
Total	4.5 a	-9.8 a	-55.9 b	-58.0 b

[a]Post-treatment data were collected one year after the last prescribed fire in 2005. Within rows, values followed by a different letter indicate significant differences ($P < 0.05$).

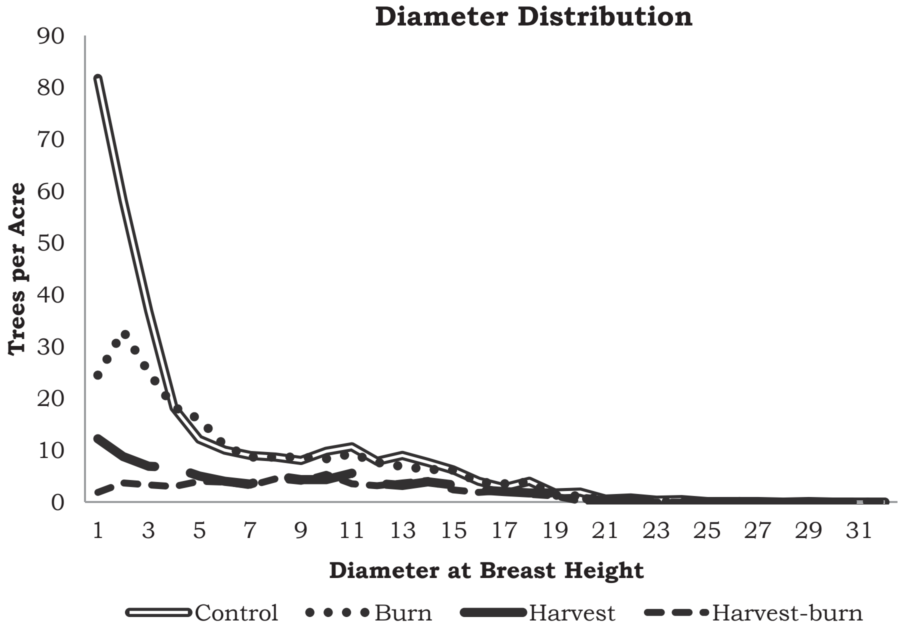

Figure 1.—Diameter distributions in inches for trees after treatment.

Changes in Ground Flora and Understory

Forb cover increased in the burn and harvest-burn treatments (Fig. 2a), indicating that the fire was a primary influence. Harvesting alone had little effect on forb cover and the change in cover was not significantly different from that of the control. Graminoid cover including grasses, sedges, and rushes increased in all treatments except for control (Fig. 2b). As with forbs, the harvest-burn treatment resulted in the greatest increase in percentage cover of graminoids (3.6%); however, this physiognomic group showed the smallest range of coverage variation between treatments. For legumes, the burn treatment had the greatest nominal increase in percentage coverage (3.7%); however, this increase was not significant (Fig. 2c).

The harvest and harvest-burn treatments increased the cover of shrubs and vines (Fig. 2d, e) but the changes were less for these life forms than for the others when compared to their non-burned analogs (i.e., burn vs. control and harvest-burn vs. harvest). The greatest change in percentage cover of any physiognomic life form within a treatment was that of woody species in control plots, which decreased by 15.9 percent but remained unchanged in the other treatments (Fig. 2f). This decrease in the control was caused by the mortality of seedling cohorts established after heavy seed crops that did not persist under a fully stocked canopy. As with changes to structure, slope position and aspect had no significant effect on the changes in the coverage of these life forms.

We grouped the ground flora into a “woodland indicators” category by using a species list of legumes, forbs, and graminoids common to Ozark Highlands woodlands created by field staff of the Missouri Department of Conservation (Table 4). Percentage cover of woodland indicators increased in the burn and harvest treatments compared to control with the greatest increases occurring in the harvest-burn treatment (Fig. 3).

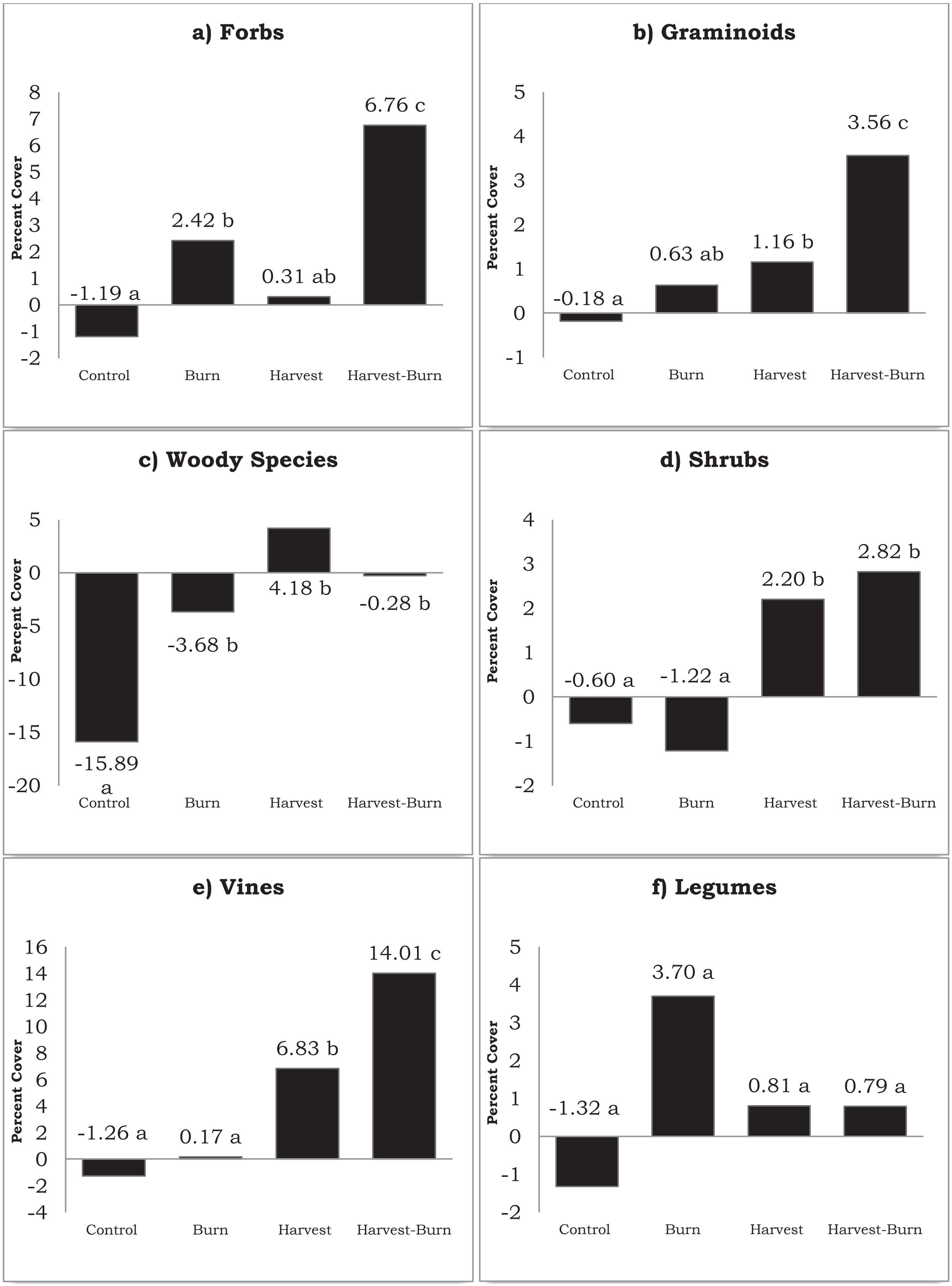

Figure 2.—Changes in percentage coverage of six physiognomic life forms. Values followed by a different letter indicate significant differences ($P < 0.05$).

Table 4.—Woodland indicator species[a] used in understory vegetation sampling

Andropogon gerardii	*Ionactis linariifolius*	*Silphium terebinthinaceum*
Asclepias tuberosa	*Lespedeza hirta*	*Solidago hispida*
Aureolaria grandiflora	*Lespedeza procumbens*	*Solidago petiolaris*
Babtisia bracteata	*Lespedeza violacea*	*Solidago radula*
Blephilia ciliata	*Lespedeza virginica*	*Solidago rigida*
Ceanothus americanus	*Liatris aspera*	*Solidago speciosa*
Comandra umbellata	*Liatris squarrosa*	*Solidago ulmifolia*
Coreopsis palmata	*Lithospermum canescens*	*Sorghastrum nutans*
Cunila origanoides	*Monarda bradburiana*	*Symphyotrichum anomalum*
Dalea purpurea	*Orbexilum pedunculatum*	*Symphyotrichum oolentangiense*
Desmodium rotundifolium	*Parthenium integrifolium*	*Symphyotrichum patens*
Echinacea pallida	*Phlox pilosa*	*Symphyotrichum turbinellum*
Eryngium yuccifolium	*Pycnanthemum tenuifolium*	*Taenidia integerrima*
Euphorbia corollata	*Schizachyrium scoparium*	*Tephrosia virginiana*
Gentiana alba	*Silene regia*	*Verbesina helianthoides*
Gillenia stipulata	*Silene stellata*	*Viola pedata*
Helianthus hirsutus	*Silphium integrifolium*	

[a]Woodland indicator species are herbaceous plants that produce flowers and seeds during the summer months, and are adapted to ecosystems where light penetration is relatively high. These species, often associated with prairie and savanna ecosystems, indicate stand density has remained sufficiently low to allow sunlight to reach the ground vegetation.

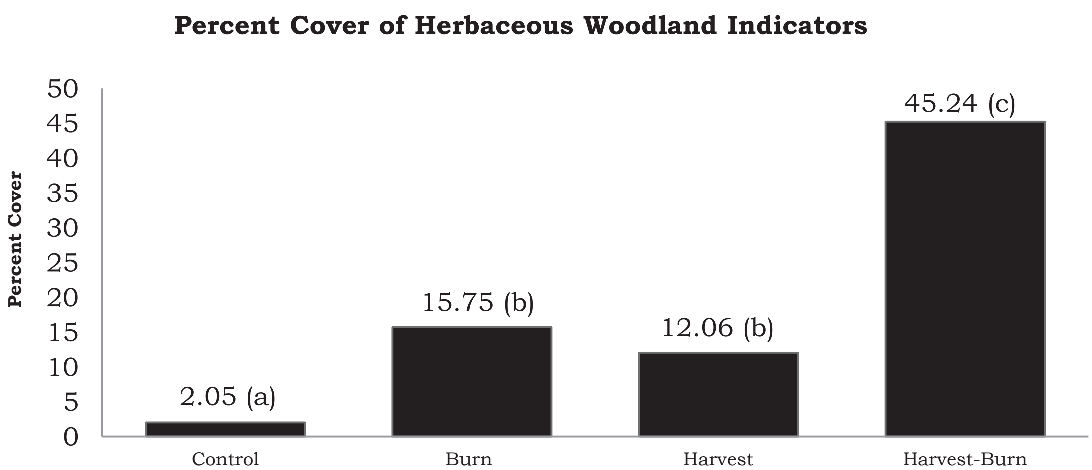

Figure 3.—Percentage coverage of woodland indicator species (see Table 4) following treatment. Values followed by a different letter indicate significant differences (P < 0.05).

DISCUSSION

The transition from what once were open-canopied oak woodland ecosystems to the present-day dense oak forest throughout the Ozarks is well documented (Ladd 1991, Nuzzo 1986). Fire suppression is thought to have facilitated increases in woody components of a stand, especially in small-diameter stems (Albrecht and McCarthy 2006, Arthur et al. 1998, Hutchinson et al. 2005, Nowacki and Abrams 2008, Peterson and Reich 2001). Our results showed that the two prescribed fires applied during a 3-year period significantly reduced stocking of small trees compared to control conditions although overall stocking decreases attributable to the burning were minor (Table 3). In stands that were harvested before burning, stocking reductions attributable to prescribed fire were smaller, mainly because the thinning was applied from below, targeting first the size classes of trees most vulnerable to mortality caused by fire (Dey and Hartman 2005).

The larger size classes of trees in our study were mostly unaffected by the prescribed fire, a result also reported by others (Albrecht and McCarthy 2006, Arthur et al. 1998, Hutchinson et al. 2005, Johnson et al. 2009). Larger-diameter trees are much less vulnerable to mortality caused by fire, allowing most of the canopy dominant and codominant trees to persist in the overstory (Brose et al. 1998, Dey and Hartman 2005, Taft 2009). This differential susceptibility to fire based upon tree diameter is thought to have led to the development of woodland structure characterized by the presence of "open-grown" large trees with a wide-spreading canopy and a relatively sparse understory and midstory (Nelson 1995, Taft 2009).

Despite only minor reductions in stocking, the two prescribed fires significantly increased the abundance of forbs, legumes, and graminoids (Fig. 2a, b, f), as well as woodland indicator species (Table 4, Fig. 3). The response of woodland indicators to the prescribed fire was about the same as in the harvest treatment, where overstory stocking was reduced to about 40 percent. This result suggests that the effects of prescribed fire were not limited to simply increasing the amount of sunlight reaching the understory. Fire reduces competition by woody species and removes some or all of the thick layers of leaf litter that can inhibit the germination of some of the woodland indicator ground flora (Nelson 2005, Stambaugh et al. 2006). In our study sites, Kolaks et al. (2004) reported that the first prescribed fire consumed more than 97 percent of the leaf litter, perhaps creating favorable conditions for herbaceous plant germination. Increasing sunlight to the ground layer played an important role in increasing the cover of woodland indicators. We found that the combination of thinning the canopy and applying fire caused the greatest response in the woodland indicators, increasing their cover three times compared to burn only, almost four times compared to harvest only, and more than 20 times compared to control.

Relative to control and burn treatments, the percentage cover of woody species, shrubs, and vines increased where stands were harvested or harvested and burned. This is an important finding considering that a dense layer of woody plants may inhibit the development of a diverse herbaceous layer. In fact, the establishment of woody seedlings, seedling sprouts, and stump sprouts may become a problem for managing the herbaceous ground flora in stands that were thinned to low stocking levels and where the fire-free interval is several years long (Taft 2009). Our data suggest that the high shade from these remaining canopy trees in the burn treatment may have helped to slow or inhibit the cover of understory woody vegetation and promoted the development of herbaceous ground flora.

It is important to recognize that these results represent the changes that have taken place during a relatively short time following the application of treatments. Forest and woodland vegetation is dynamic and rapid changes in the cover of the understory are anticipated. Thus woodland management should be considered a continuous process requiring the application of prescribed fire and possibly thinning treatments on a regular basis to prevent the woody cover from becoming dominant in the midstory and understory layers (Albrecht and McCarthy 2006, Arthur et al. 1998, Brose et al. 1998, Johnson et al. 2009). Future work in this study will focus on the dynamic nature of restored woodlands and on the changes that take place during fire-free intervals.

It is also important to recognize that at some point in time, management actions may be necessary to ensure trees can be recruited into the overstory to replace those that die or that are harvested. These actions may require creating canopy openings by harvesting some or all of the overstory and by maintaining fire-free intervals to allow seedlings to grow large enough to survive when the prescribed fire regime is reinstituted. Although beyond the scope of this study, recruiting seedlings in managed woodlands is an important consideration if sustaining the composition and structure of the overstories of these unique ecosystems is a management objective.

CONCLUSIONS

The application of prescribed fire for restoring and managing woodlands was found to cause minor changes to forest structure primarily by reducing the stocking of trees <5 inches d.b.h. Despite these minor changes, the prescribed fire significantly increased the cover of forbs, graminoids, and other plant species considered indicators of woodland composition. The effect of prescribed fire on woodland indicators was about the same as thinning stands to 40 percent stocking, underscoring the important effects of prescribed fire for maintaining woodland composition. However, harvesting alone also increased the cover of woody regeneration, shrubs, and vines – lifeforms that can prohibit the development of herbaceous plants in woodlands. The greatest response of the ground flora, particularly woodland indicator plants, occurred with the combination of harvesting and prescribed burning. This result suggests that increased sunlight to the ground layer, the removal of leaf litter, and the reduction of woody competition are the most beneficial to woodland plants. However, it is likely that the density of woody reproduction will rapidly increase under low overstory stocking if fire is not applied on a frequent basis.

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THE CASE FOR DELAYING PLANTING OF BOTTOMLAND OAKS: AN EXAMPLE INVOLVING NUTTALL OAKS

David C. Mercker, David S. Buckley, and John P. Conn[1]

Abstract.—A prominent difficulty during bottomland hardwood afforestation in the southeastern United States is that sites are often flooded during the preferred months of planting (January - March), which results in delayed planting (April - June) and reduced survival. We monitored growth and survival of Nuttall oak (*Quercus texana* Buckley) seedlings planted in 11 months (February through December) after varying periods of humidified cold storage to investigate the hypothesis that seedlings held over the summer months in humidified cold storage and planted in autumn months would fare better than seedlings planted in late spring and summer. Results generally agreed with this hypothesis. A trade-off is that height growth decreased with increased periods of time in cold storage. These results suggest that although reduced height growth can initially be expected, long-term storage over the summer months and subsequent planting in autumn need not result in substantial mortality of Nuttall oak. Differences in height may become less significant with each successive growing season.

INTRODUCTION

Over the past century, a considerable amount of bottomland forest has been deforested and drained for row crop farming throughout the southeastern United States (MacDonald et al. 1979, Turner et al. 1981). Since the 1980s, natural resource professionals and federal and state agencies have focused on restoring portions of these cleared areas to native hardwood trees through various conservation programs (Stanturf et al. 2001). Restoration of bottomland hardwoods has been a recent focus in the management of agricultural wetlands in Tennessee (Johnson 2007).

Professional foresters and contractors often follow conventional tree planting procedures that are well established for upland sites, but prove problematic in bottomlands. High water tables, poor soil drainage, overland flooding, and diverse soil properties make tree planting difficult during the commonly accepted optimum planting period between mid-winter and mid-spring (January through April). These hydrologic obstacles often cause seedlings to be planted in late spring and summer (from May on). Late planting results in poor survival. In some cases the sites may go unplanted, leading to disposal of seedlings and a follow-up attempt to plant the next year.

A previous investigation involving upland hardwood seedlings suggested that increasing the length of time in cold storage decreases post-planting root growth and percent bud break, and increases stem dieback and mortality (Englert et al. 1993). We investigated whether results would be similar with bottomland species on a bottomland site. Our hypothesis was that seedlings held over the summer months in cold storage and planted in autumn months would fare better than seedlings planted in late spring and summer.

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STUDY AREA

The study was conducted on the University of Tennessee's West Tennessee Research and Education Center (WTREC), located in Jackson, Tennessee. The site is located adjacent to the South Fork of the Forked Deer River (35º 37'34" N, 88º51'22" W, 120 m mean elevation). It includes a 122 m by 122 m section nested within a larger 49-ha bottomland area that underwent afforestation in winter 2004. The predominant soil type is Waverly silt loam (0- to 2-percent slope), which is deep and poorly drained (Sease and Springer 1957). Flooding of the site occurs five to six times per year and inundation often lasts several days. The site was used for row crop farming until 2004, when it was enrolled into the Conservation Reserve Program.

METHODS

Nuttall oak (*Quercus texana* Buckley) was selected because this species was previously found to be tolerant of extended inundation on the site available for this study (McCurry 2006). All seedlings planted were 1-0 stock and were grown at the Tennessee Department of Agriculture, Forestry Division, East Tennessee Nursery in Delano, Tennessee.

Seedlings were lifted during the first week of January and shipped on January 5, 2007. They were picked up on January 8, 2007. Prior to shipping from the nursery, seedlings were graded so that all had root collars greater than 0.6 cm caliper. The roots were dipped in Viterra root dip (potassium propenoate propenamide copolymers, Amereq, Inc., New City, NY) to conserve moisture. The Viterra root dip was mixed at a rate of 3.75 g per L of water. After dipping, seedlings were packaged (without mulch) into 4-mil plastic bags, then placed into triple-ply craft paper with a poly-coated inner lining. Each ply was 50-lb. craft paper. After arrival, the seedlings were stored in a humidified cold room with temperature and relative humidity set at 2.2 ºC and 94 percent, respectively. A 30-hour power outage occurred unexpectedly on August 24-25, 2007. The maximum temperature in the cold room during the outage reached 25.2 ºC with an average of 19.6 ºC. The relative humidity dropped to a low of 82 percent.

Initial height measurements were taken to the nearest cm using a custom-made polyvinyl chloride pipe with markings graduated in centimeters. The average aboveground height at the time of planting, measured from ground to terminal bud, was 51 cm (S.E. = 0.5). Initial stem caliper was also measured with a Plasti-cal Digital Caliper (Mitutoyo, Kawasaki, Japan) to the nearest 1 mm at ground level. The average caliper was 8 mm (S.E. = 0.1).

The study was established as a randomized complete block design with all treatments appearing once in each of three blocks established in relation to elevation of the site. No attempt was made to select uniform stock from within the bundles, nor was there any culling of very small or very large seedlings (other than what occurred at the nursery). Twelve treatments, corresponding to plantings in every month of the year, were assigned at random to 12 plots within each block, resulting in 36 plots with 720 seedlings for the entire study (Fig. 1). A single row containing 20 Nuttall oak seedlings on 1-m spacing was established in each plot. With a total of three replications, 60 Nuttall oak seedlings were planted per month. Seedlings for each month were planted successively between 7:00 a.m. and 10:00 a.m. and between the 10th and 20th day of any given month. No seedlings could be planted during January at the outset of the study in 2007 because the site was flooded. As a result, the January treatment was dropped from the study.

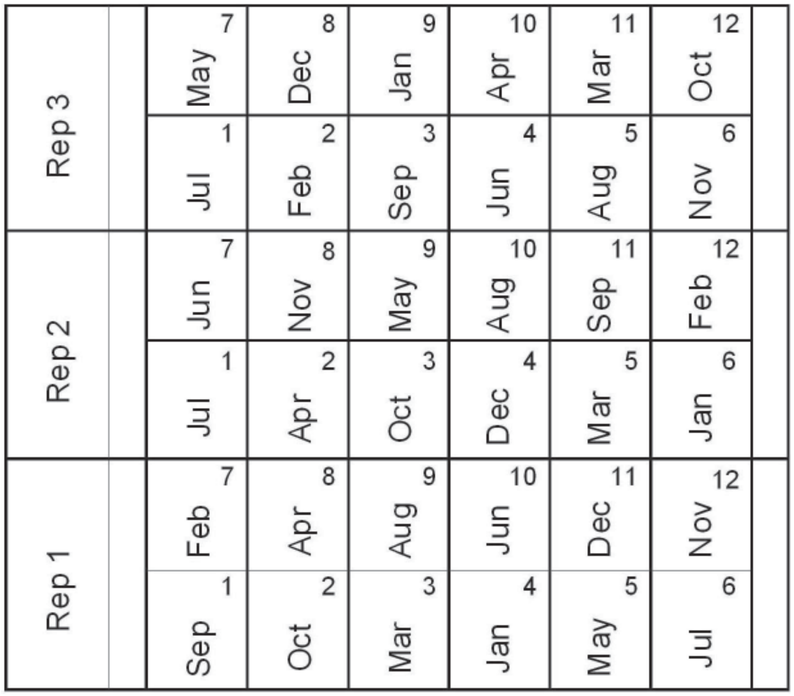

Figure 1.—Study design.

Site preparation, conducted in August 2006, consisted of a single application of a 2 percent solution of active ingredient (glyphosate) of Roundup® (Monsanto, St. Louis, MO) in 76-cm bands applied directly over the designated rows. In addition, during the year of planting (2007) and the next 2 years, planted rows were side-dressed with the same herbicide at the same rate, once per month (April through September). The band width was 38 cm on both sides of every row. Weeds were controlled carefully throughout the entire study to minimize effects of differences in the abundance of competing vegetation over the time period of the study. Mowing between the rows occurred each month during the growing seasons. Survival and seedling heights were recorded in September of 2008 and 2009, and in October 2010. Seedlings were considered dead if there was no indication of living tissue above ground. Scratch testing to reveal green cambium was conducted on questionable seedlings.

Data were analyzed through one-way analysis of variance (ANOVA) and analysis of covariance (ANCOVA) with models appropriate for a randomized complete block design. The general linear models procedure (SAS Institute, Cary, NC) was used. Pairwise comparisons were conducted between months with Tukey's honestly significant difference ($\alpha = 0.05$). The degree to which assumptions underlying ANOVA and ANCOVA were met was investigated using the univariate procedure (SAS Institute). The normal probability plot and Shapiro-Wilk statistic and associated p-value yielded by the univariate procedure suggested that it was reasonable to assume that the survival percentage data came from a population with a normal distribution ($W = 0.94$ and $Pr < W = 0.0657$). As a result, survival percentage data were not transformed before analysis. Similarly, results yielded by the univariate procedure for the height data suggested that no transformations of these data were necessary ($W = 0.99$ and $Pr < W = 0.0743$). Analyses of height data for 2010 were conducted with and without 2007 heights and 2007 caliper measurements as covariates. Patterns in significant differences among months were identical between both types of analysis. All analyses were conducted using SAS, Version 9.2 (SAS Institute, Inc., Cary NC).

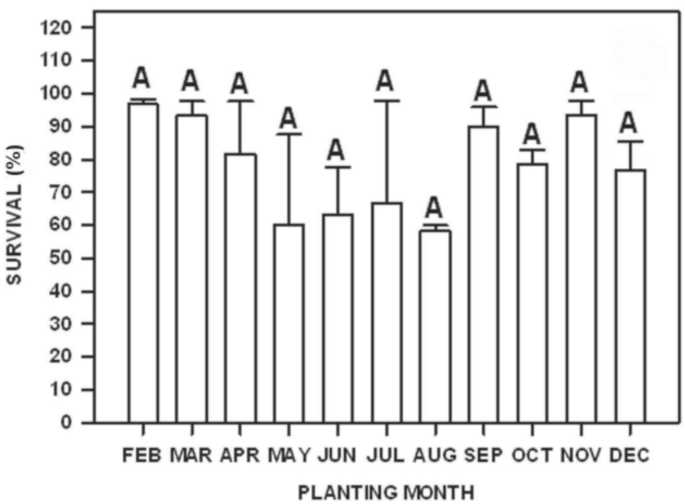

Figure 2.—Mean percent survival of Nuttall oak as of September 2010 by planting month treatment. Bars with the same letters are not significantly different at the alpha=0.05 level. Error bars represent 1 standard error.

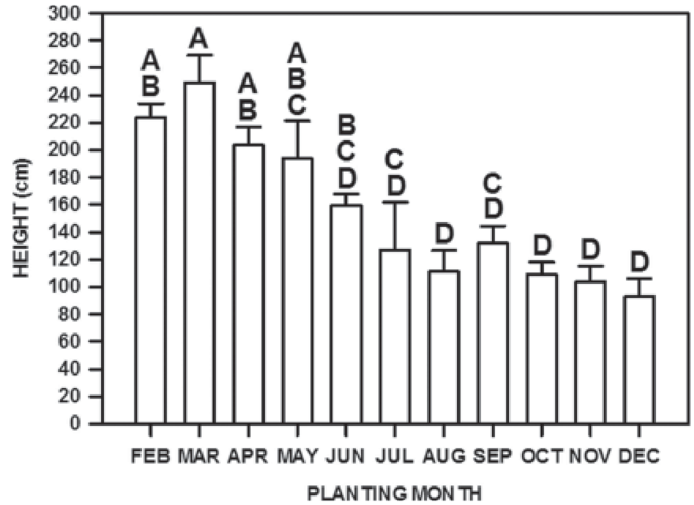

Figure 3.—Mean height of Nuttall oak as of October 2010 by planting month treatment. Bars with the same letters are not significantly different at the alpha=0.05 level. Error bars represent 1 standard error.

RESULTS

As of September 2010, mean survival rate calculated across all treatments and sample periods was 78 percent (Fig. 2). Analysis of variance suggested significant differences in mean survival rate among months ($p = 0.0164$), but Tukey's honestly significant difference did not. It should be noted, however, that Tukey's honestly significant difference indicated that February survival was significantly different from August survival when the highly variable May and July survival data were omitted from the analysis. Based on the magnitudes of the means, survival was favorable in the February through April planting treatments, averaging 91 percent. Survival was less favorable during the late spring and summer period (May through August), averaging 62 percent. Survival rate for the final planting period (September through December) rebounded, averaging 85 percent.

Mean seedling height differed among planting months ($p < 0.0001$) and decreased from early to late planting dates (Fig. 3, Table 1). However, the year-over-year percentage difference in height narrowed with each successive year. For instance, when observing height measurements over the duration of the project, we found in 2008 that February- through April-planted seedlings were 233 percent taller than September- through December-planted seedlings in 2008, 226 percent taller in 2009, and 204 percent taller in 2010. Although data on resprouting were not formally collected, resprouting of late-planted seedlings was observed to be more prevalent than early-planted seedlings and likely explains the decrease in height from 2007 to 2008 in the later months. This trend reversed in 2009.

Table 1.—Height (cm) of Nuttall oak (2007 - 2010)

Month	2007	2008	2009	2010
Jan	n/a	n/a	n/a	n/a
Feb	48	82	167	224
Mar	58	110	200	251
Apr	50	78	149	206
May	49	82	155	209
Jun	51	55	110	163
Jul	46	53	113	159
Aug	51	34	81	112
Sep	55	51	100	132
Oct	54	41	77	110
Nov	48	34	63	105
Dec	49	29	66	97

DISCUSSION

This study is not a definitive test of the hypothesis that holding seedlings in a humidified cold room over the summer months, and then planting them during the autumn months, is a viable solution to the problem of early season flooding of bottomland restoration sites. The findings do suggest, however, that in the case of Nuttall oak, it is at least possible to have acceptable survival rates (80 percent or better) with seedlings planted in September through December.

The potential effects of two occurrences during the study should be noted. First, during the year of implementation (2007), the west Tennessee region experienced an extreme drought. Eight months received below-normal precipitation in 2007, and year-end total precipitation was 33.4 cm below normal. During the growing season, May through August, the precipitation deficit was 31.3 cm (National Oceanic and Atmospheric Administration 2009). The drought could have increased mortality overall, particularly in the summer months. Secondly, the power outage that occurred for 30 hours in August, allowing the temperature in the cold room to climb to 25.2 °C, may have influenced seedling viability. If these events had not taken place during the study, survival could have been greater for all planting dates.

Survival was greatest in the early spring planting period, was less favorable in the late spring/summer period, but then rebounded in the autumn period. Results confirm that, at least within the first four growing seasons, height growth is suppressed by delayed planting. However, the percentage difference in height between these two groups declined with each successive year. This result suggests that early height differences could become less substantial over the duration of the rotation. Initial growth can be important, however, in influencing the competitive status of planted seedlings relative to other vegetation.

The promising results obtained for Nuttall oak in this study suggest that additional research involving the performance of delayed plantings of other species used in bottomland hardwood restoration is warranted. Examination of the viability of a range of seedling size classes for an expanded set of species stored for various periods of time in a cold room is planned.

ACKNOWLEDGMENTS

Our study was funded by the Department of Forestry, Wildlife and Fisheries; the University of Tennessee Extension; and the West Tennessee Research and Education Center (WTREC) of the University of Tennessee Institute of Agriculture. Seedlings were supplied by the Tennessee Division of Forestry, East Tennessee Nursery. The restoration project was made possible by the Natural Resources Conservation Service through a Conservation Reserve Program agreement under the Forested Riparian Buffer Practice. We especially thank R. Hayes, G. Percell, and R. Staggs at WTREC for assistance with study implementation.

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IMPACT OF PROFESSIONAL FORESTERS ON TIMBER HARVESTS ON WEST VIRGINIA NONINDUSTRIAL PRIVATE FORESTS

Stuart A. Moss and Eric Heitzman[1]

Abstract.—Timber harvests conducted on 90 nonindustrial private forest properties in West Virginia were investigated to determine the effects that professional foresters have on harvest and residual stand attributes. Harvests were classified based on the type of forester involved: (1) consulting/state service foresters representing landowners, (2) industry foresters representing forest products firms, and (3) no involvement by a professional forester.

Consulting foresters removed less volume and value from the stand, caused a smaller decrease in average tree diameter, and displayed a lower preference for harvesting the more valuable species. Residual stands resulting from consultant harvests were more likely to be fully stocked, contain higher proportions of acceptable growing stock, and suffer less logging damage. There were few differences between harvests conducted by industry foresters and nonforesters.

Harvests were given overall evaluations based on residual stand attributes. Nearly one-fourth of the consultant harvests received a "good" evaluation, compared to less than 10 percent of industry forester harvests and no harvests when a forester was not involved. Less than one-fourth of the consultant harvests received a "poor" evaluation, compared to one-half to two-thirds for the other two groups.

INTRODUCTION

Approximately 60 percent (7.4 million acres) of West Virginia's forest land is classified as nonindustrial private forest (NIPF) land, commonly referred to as "family forests" (Widmann et al. 2010). Timber production is not a primary ownership objective for many West Virginia timberland owners (Fraser and Magill 2000, Joshi 2007), a sentiment echoed in other eastern states (Hodge and Southard 1992, Olson 1979). In the most recent survey of West Virginia NIPF landowners, only 10 percent listed timber production as "very important" or "important" reasons for owning forest land (Widmann et al. 2010). However, these landowners owned nearly one-third of the state's forests. In addition, a survey conducted in 1999-2000 indicated that 44 percent of the state's NIPF landowners had harvested timber from their land at some time(Fraser and Magill 2000).

Because NIPF landowners control such a large portion of the resource, their management, or lack thereof, of their land is a factor critical to the future timber supply, the provision and enhancement of nontimber forest resources, and the protection of soil and water quality. Nearly half of the NIPF landowners in West Virginia who harvested timber during 2000-2001 did so without the assistance of a professional forester (McGill et al. 2006). Such results support the belief among the forestry community that poor forest practices are used on a great many acres in the state. Foresters have long argued that involvement by a professional forester in the timber sale process can benefit landowners. Foresters can use their knowledge of silviculture and other facets of the profession to best meet

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landowners' objectives for their forests and are more likely to leave a "better" residual stand after harvesting that will yield increased future benefits, financial and otherwise, for the landowner.

Despite the apparent validity of these widely held views, there is scant evidence to support these claims in the Appalachian region. Rather grim assessments of harvesting practices among NIPF landowners in New York, Pennsylvania, and West Virginia indicate that many landowners cut their largest, most valuable trees and leave the less valuable trees after harvest, regardless of whether a forester is involved with the harvest (Fajvan et al. 1998; Nyland 1992, 2001; Pell 1998). More recently, a survey of NIPF landowners who harvested timber in West Virginia found that 62 percent of the harvests were conducted by using a diameter-limit cut, even though professional foresters were involved with 60 percent of the harvests (McGill et al. 2006). This type of practice—harvesting without regard to silviculture—is exactly the type of practice that is supposedly avoided when professional foresters are consulted.

An important factor not addressed in previous studies of forester involvement in harvesting is whether or not the forester represents the landowner (i.e., a private consulting forester or state service forester) or represents the buyer (i.e., a procurement or management forester employed by a forest products firm). The relationship between the forester and landowner could significantly influence how the forester conducts the harvest. Because the interests of consulting/service foresters are more closely aligned with those of the landowner, it stands to reason that a consulting/service forester might conduct the sale and impact the residual stand in a much different manner from a forester working for the purchaser, whose interests may run contrary to the landowner's. However, there have been no studies in the Appalachian hardwood region to test this hypothesis.

STUDY AREA

This study was conducted on 90 forested sites throughout West Virginia. All sites were owned by NIPF landowners and had been subjected to partial timber harvesting between January 2005 and June 2007.

METHODS

This project was designed to compare partial timber harvests conducted by three groups: (1) consulting/state service foresters, (2) industry/procurement foresters, and (3) nonforesters. Post-harvest inventories of these properties (30 for each forester type) were conducted to measure attributes of the residual trees (species, size, value, quality, amount of logging damage); estimate the species, volume, and value of timber harvested; and assess the characteristics of the harvest (percentage of basal area, volume and value removed, change in quadratic mean diameter [QMD] and stocking level).

This project was restricted to evaluating the impact professional foresters have on partial timber harvests. Because virtually all merchantable timber is removed during a clearcut harvest, it is unlikely foresters would exert much influence on either the trees that are harvested or the residual stand composition. In addition, our analysis of timber harvest notifications provided by the West Virginia Division of Forestry (WVDOF) indicates that more than 90 percent of timber harvests in the state are some form of partial harvest, so foresters' impact on these types of harvests is most relevant.

Sample Selection

Excel® spreadsheets (Microsoft, Redmond, WA) containing information on all timber harvests in West Virginia which began during 2005 and 2006 were provided by the WVDOF. This list was pared to include only partial harvests of at least 20 acres in size on properties owned by NIPF landowners. The NIPF classification excludes forest land owned by government entities, forest products manufacturing firms, and other industrial owners. In addition, we excluded properties owned by real estate investment trusts and timberland investment management organizations. Every landowner on the timber harvest list was contacted by mail to: (1) verify that a timber harvest occurred on the land, (2) determine what type of forester, if any, was involved in the sale, and (3) request his or her willingness to participate in the study by allowing us to inspect and collect inventory data from the property. Within 3 months, 273 landowners (11 percent) had agreed to participate in the study.

To ensure that samples were well-distributed throughout the state, properties were divided into six groups according to the former WVDOF management districts in which the properties lie. Within each district, we randomly selected: (1) five properties for which the landowner indicated he or she had used a consulting/state service forester to assist with the sale, (2) five properties for which the landowner indicated that only an industry/procurement forester was involved in the sale, and (3) five properties for which the landowner indicated that no professional forester was involved. After initial selection of the properties, both information provided by the landowner and information provided on the timbering operation notification forms were scrutinized to ensure that the forester classification provided by the landowner was correct. The following criteria were used to classify each sale according to the type of professional involved:

1) Consulting forester – an individual or firm that provides forest management consulting services to the public, for a fee. Such individuals must be registered professional foresters (or forest technicians) in West Virginia and must not be employed by forest products companies or engage in the buying and selling of timber or timberland for themselves or on behalf of their employer. Foresters employed by forest products companies that also provide consulting services and foresters involved with industrial landowner assistance programs were specifically excluded from this classification.
2) State service forester – an individual employed by the WVDOF who is also a registered professional forester (or forest technician) in West Virginia.
3) Industry/procurement forester – any registered professional forester (or forest technician) not classified as a "consulting forester" or "state service forester."
4) Nonforester – an individual who does not meet any of the above criteria.

"Registered professional forester" and "registered forest technician" status was verified using membership rosters provided by the West Virginia State Board of Registration for Foresters.

Field Measurements

Circular 0.1-acre inventory plots were established throughout each selected property on a systematic grid. Sampling intensity was one plot per harvested acre, with a minimum of 20 plots and a maximum of 30 plots on each property. Sampling was confined to recently harvested areas. Tree species, stem diameter at 4.5 feet from the ground (diameter at breast height, d.b.h.), and canopy position (dominant/codominant, intermediate, or suppressed) were measured for all living residual trees ≥4.6 inches d.b.h. On every third plot, stump diameter was measured for every residual tree. These data were collected to develop regression equations to predict d.b.h. from stump diameter.

Each tree was evaluated for future sawtimber potential, following guidelines for the U.S. Department of Agriculture, Forest Service tree grades, based on the number and severity of defects within the butt log (Miller et al. 1986). Trees with potential to make Forest Service tree grades of F1 or F2 were considered "acceptable growing stock." Various types of logging damage (damage to bole, damage to crown, broken or leaning stem) were noted for each residual tree.

Species, stump height, and stump diameter (average of two measurements) were recorded for every recently harvested stump ≥6 inches in average diameter located within the 0.1-acre sample plots. On 39 properties, trees to be harvested had been designated as such with tree-marking paint (29 of 30 consulting forester sales, 8 of 30 industry forester sales, and 2 of 30 nonforester sales). On these sites, marked trees that were left unharvested by the logger were considered to be "harvested" and their d.b.h. was measured directly, rather than being estimated from stump diameter. This step was taken to ensure that the project evaluated forester performance (how the forester intended to harvest the site) rather than logger performance (how the site was actually harvested). The incidence of unharvested marked trees was extremely low (65 trees out of 5,934 stumps + marked residuals, or just over 1 percent).

In all, 2,346 plots were placed on 90 properties in 21 counties. A total of 21,648 residual trees and 5,934 stumps (including marked residual trees) were measured. Based on our field measurements, all properties examined in this study appeared to have been well-stocked with merchantable sawtimber prior to harvesting. No evidence was found of harvest activity before the most recent harvest on any subject property.

Data Analysis

Stump diameters and d.b.h. measurements from the residual trees were used to develop species-specific linear regression equations to predict d.b.h. from stump diameter. Coefficients of determination (R^2) for the regression equations were above 0.92 for all species. These equations were used to predict the d.b.h. of harvested trees on the sample plots by using the measured stump diameters from the harvested trees.

Merchantable stem volumes for residual and harvested trees were predicted from d.b.h. (for residual trees) or predicted d.b.h. (for harvested trees) by using equations from Wiant (1989). Cubic-foot volumes were calculated for all trees with an actual or predicted d.b.h ≥4.6 inches. International 0.25-inch scale board-foot volumes were calculated for all trees with an actual or predicted d.b.h. ≥11.6 inches. Percentage of stocking was calculated for each property by using stocking charts for upland Central Hardwoods (Gingrich 1967).

Stumpage value was calculated for all trees with an actual or predicted d.b.h. ≥11.6 inches by using stumpage prices in dollars per thousand board feet (MBF) (International 0.25-inch scale) reported by the West Virginia University Appalachian Hardwood Center (AHC) for 2007 (statewide average of the four quarterly reporting periods). For stumpage value calculations, species were grouped into the following AHC pricing categories:

1) northern red oak (*Quercus rubra* L.)
2) white oak (*Q. alba* L.)
3) mixed oak: all oaks except northern red and white oak
4) black cherry (*Prunus serotina* Ehrh.)
5) yellow-poplar (*Liriodendron tulipifera* L.) and cucumbertree (*Magnolia acuminata*)
6) hard maple: sugar maple (*Acer saccharum* Marsh.) and black maple (*A. nigrum*)
7) soft maple: red maple (*A. rubrum* L.) and silver maple (*A. saccharinum*)
8) ash: all (*Fraxinus* spp.)
9) hickory: all (*Carya* spp.)
10) black walnut (*Juglans nigra*)
11) other species: all species not otherwise categorized

Analysis of variance was performed to determine the effect of forester type (consultant, industry, or none) on various harvest and residual stand attributes ($\alpha = 0.10$). The Tukey-Kramer multiple-comparison test was performed on treatment means to determine significant treatment differences ($\alpha = 0.10$).

Properties were grouped into classes based on various harvest removal and residual stand attributes. For example, each property was assigned to the appropriate residual damage class based on the percentage of the residual basal area damaged, either: (1) ≤10 percent damaged, (2) 11 to 15 percent damaged, or (3) ≥16 percent damaged. The number of properties falling into each class was summed for each forester type. Pearson's chi-square goodness-of-fit test was performed to determine if differences in observed frequencies between the forester types were significant.

Finally, an overall harvest evaluation was performed for each property based on three residual stand attributes: (1) stocking classification, (2) percentage of residual basal area classified as acceptable growing stock, and (3) percentage of residual basal area damaged. These criteria were judged by professional foresters to be the three most useful silvicultural attributes for assessing harvesting impacts on a site (Egan and Jones 1997). Together, these three factors significantly affect the quality of the residual stand and the likelihood that the stand will produce high-quality timber in the next 10 to 20 years.

Properties were evaluated for each of the above attributes based on criteria outlined in Table 1. Each attribute was rated as "good," "fair," or "poor" based on these criteria and points were assigned to each property based on these evaluations. These three scores were summed and properties with a total score of 5 or 6 points received an overall evaluation of "good." Properties with a total score of 3 or 4 points received an overall evaluation of "fair." Those with 2 or fewer total points received an overall evaluation of "poor." No residual stands were overstocked, so no evaluation criterion was necessary for overstocked conditions.

Table 1.—Criteria used to perform an overall harvest evaluation on 90 NIPF properties in West Virginia

Stand attribute	Good (2 points)	Fair (1 point)	Poor (0 points)
Gingrich stocking classification	Fully stocked	Understocked	Severely understocked
Basal area in acceptable growing stock	61% or greater	41 to 60%	40% or less
Basal area damaged	10% or less	11 to 15%	16% or greater
Overall evaluation	5 – 6 points	3 – 4 points	0 – 2 points

Table 2.—Mean values, by forester type, for harvest removal attributes on 90 NIPF properties in West Virginia

	Forester type		
Harvest attribute	Consultant	Industry	None
Sawtimber basal area harvested	57.7% a[†]	67.8% b	68.8% b
Sawtimber volume harvested	60.1% a	70.5% b	71.2% b
Sawtimber value harvested	58.9% a	70.2% b	71.2% b
Species preference ratio	0.98 a	1.00 b	1.01 b

[†] Means within a row followed by the same letter are not significantly different ($\alpha = 0.10$).

For example, a property that was fully stocked with 52 percent of the residual basal area classified as acceptable growing stock and 20 percent of the residual basal area damaged would receive a stocking classification rating of "good" (2 points), an acceptable growing-stock rating of "fair" (1 point), and a damage rating of "poor" (0 points). A total of 3 points would be assigned to this property and its overall evaluation would be "fair."

The number of properties falling into each overall evaluation class was summed for each forester type. Pearson's chi-square goodness-of-fit test was performed to determine if differences in observed frequencies between the forester types were significant.

RESULTS

Consulting foresters removed smaller proportions of trees, basal area, sawtimber volume, and sawtimber value than either industry foresters or loggers working without direction from a professional forester (Table 2). There were no significant differences between industry foresters and nonforesters for any of the harvest removal attributes examined in this study.

The species preference ratio (harvest value per MBF divided by initial value per MBF) indicates whether the harvested species were, on average, more valuable (ratio >1), less valuable (ratio <1), or of equal value (ratio = 1) compared to the initial species composition. The species preference ratio for sales handled by consulting foresters is 0.98, indicating that harvested species were slightly less valuable than the overall species composition. The species preference ratios for sales handled by industry foresters and nonforesters were 1.00 and 1.01, respectively, indicating that harvested species were as valuable as or slightly more valuable than the average species in the stand.

Residual stands resulting from harvests conducted by consulting foresters contained higher proportions of dominant and codominant trees and acceptable growing stock than properties harvested under the direction of industry foresters or nonforesters (Table 3). Consultant-directed harvests resulted in less damage to the residual stand and reduced QMD by a smaller percentage.

Table 3.—Mean values, by forester type, for residual stand attributes on 90 NIPF properties in West Virginia

Residual stand attribute	Forester type: Consultant	Industry	None
Basal area dominant or codominant	61.7% a†	51.9% b	52.2% b
Basal area in acceptable growing stock	63.0% a	57.0% b	53.2% c
Basal area damaged	14.9% a	20.7% c	17.7% b
Change in quadratic mean diameter	- 16.5% a	- 20.2% b	- 20.2% b

† Means within a row followed by the same letter are not significantly different ($\alpha = 0.10$).

Table 4.—Mean values, by forester type, for stocking parameters on 90 NIPF properties in West Virginia

Stocking parameter	Forester type: Consultant	Industry	None
Initial stocking	85.7% a†	81.8% a	82.2% a
Residual stocking	50.3% a	43.7% a	44.0% a
Change in stocking level	- 41.6% a	- 47.5% b	- 46.5% ab

† Means within a row followed by the same letter are not significantly different ($\alpha = 0.10$).

Table 5.—Percentage of basal area harvested from 90 NIPF properties in West Virginia by species and diameter class, for each type of forester involved with the harvest

	High-value species				Low-value species			
	N. red oak		White oak		American beech		Sweet birch	
Forester type	12-15 inches	≥16 inches	12-15 inches	≥16 inches	12-15 inches	≥16 inches	12-15 inches	≥16 inches
Consultant	12%	76%	14%	66%	66%	64%	44%	88%
Industry	29%	89%	22%	89%	14%	29%	0%	NA†
None	22%	87%	10%	82%	13%	32%	10%	0%

† No sweet birch ≥16 inches was tallied on any tracts harvested by industry foresters.

Properties harvested under the direction of industry foresters contained larger proportions of damaged trees compared to properties harvested without a forester's involvement. However, properties harvested under the direction of industry foresters also contained a higher proportion of acceptable growing stock compared to properties harvested by nonforesters.

Initial and residual stocking levels were not significantly different between the different forester types (Table 4). However, consulting foresters caused a smaller percentage reduction in average stocking level compared to industry foresters.

In general, consultants removed a lower proportion of high-value species (e.g., northern red oak and white oak) ≥16 inches in d.b.h, compared to the other two groups (Table 5). Industry foresters and nonforesters removed more than 80 percent of the basal area of high-value species ≥16 inches in d.b.h. Consulting foresters tended to remove considerably less basal area from the smaller diameter classes of high-value species. Consulting foresters also removed much higher proportions of low-value species (e.g., American beech [*Fagus grandifolia* Ehrh.] and sweet birch [*Betula lenta* L.]) across all merchantable diameter classes. Industry foresters and nonforesters generally avoided harvesting low-value species.

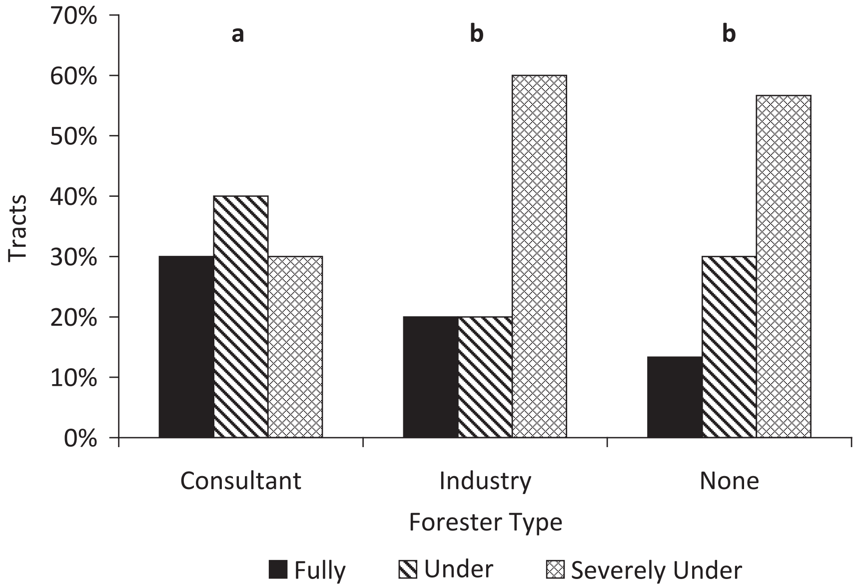

Figure 1.—Harvested NIPF properties in West Virginia classified into residual stocking classes by type of forester involved with the harvest. Forester type distributions with the same letter are not significantly different based on Pearson's chi-square goodness-of-fit test ($\alpha = 0.10$).

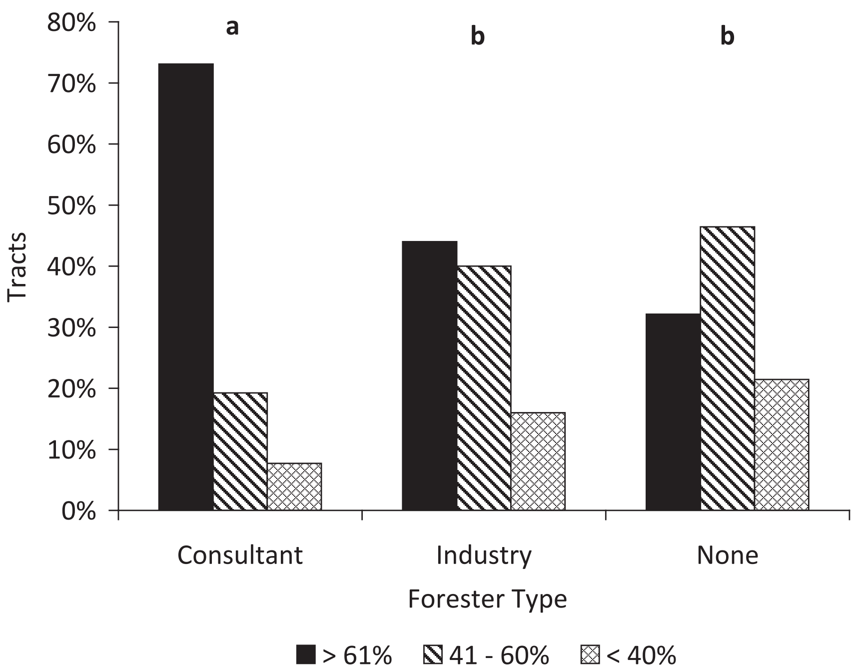

Figure 2.—Harvested NIPF properties in West Virginia classified into acceptable growing-stock classes by type of forester involved with the harvest. Forester type distributions with the same letter are not significantly different based on Pearson's chi-square goodness-of-fit test ($\alpha = 0.10$).

Thirty percent of the harvests handled by consultants resulted in residual stands that were fully stocked, compared to 20 percent or fewer of the harvests handled by industry foresters or nonforesters (Fig. 1). More than half of the harvests handled by industry foresters or nonforesters resulted in severely under-stocked residual stands, compared to only 30 percent of harvests conducted by consulting foresters.

Nearly three-fourths of the harvests conducted by consulting foresters resulted in residual stands with more than 60 percent of the residual basal area in acceptable growing stock (Fig. 2). In contrast, fewer than half of the sales handled by industry foresters or nonforesters had more than 60 percent of the residual stand in acceptable growing stock.

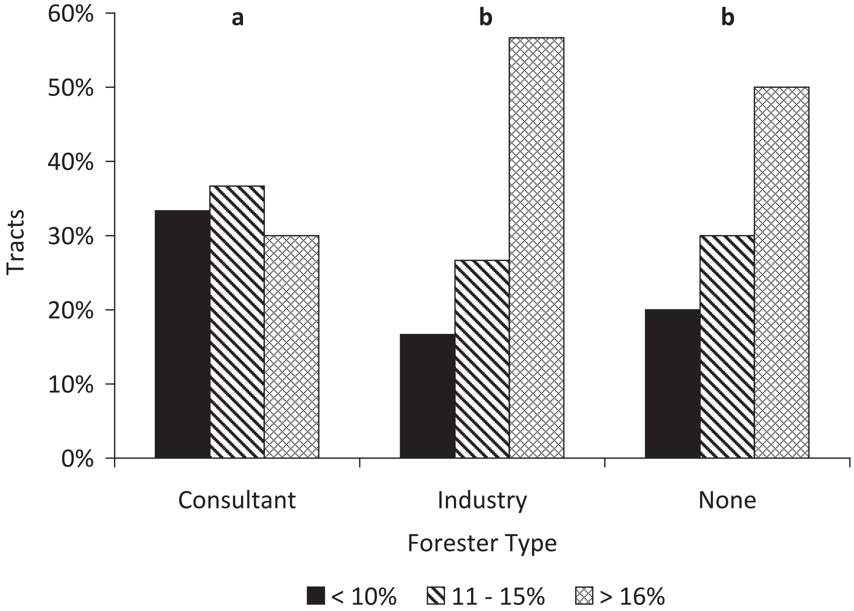

Figure 3.—Harvested NIPF properties in West Virginia classified into residual logging damage classes by type of forester involved with the harvest. Forester type distributions with the same letter are not significantly different based on Pearson's chi-square goodness-of-fit test (α = 0.10).

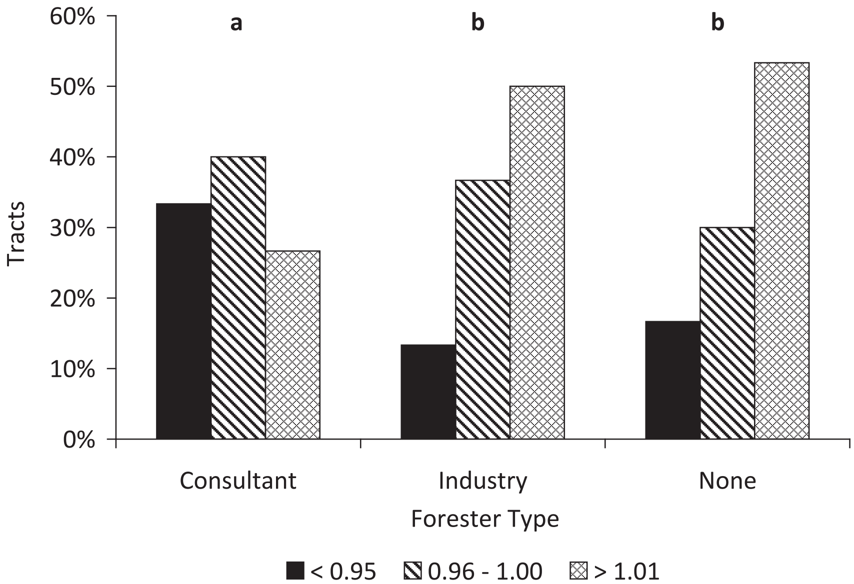

Figure 4.—Harvested NIPF properties in West Virginia classified into species preference ratio classes by type of forester involved with the harvest. Forester type distributions with the same letter are not significantly different based on Pearson's chi-square goodness-of-fit test (α = 0.10).

One-third of the harvests handled by consultants had no more than 10 percent of the residual basal area damaged by logging, whereas fewer than 20 percent of the harvests handled by industry foresters and nonforesters had such low levels of residual damage (Fig. 3). Only 30 percent of the consultants' harvests resulted in heavily damaged residual stands (at least 16 percent of the residual basal area damaged), compared to more than half of the industry forester and nonforester harvests.

Only about one-fourth of the consulting foresters displayed a preference for removing the more valuable species during harvest, as indicated by a species preference ratio greater than 1.0 (Fig. 4). In contrast, more than half of the industry foresters and nonforesters indicated a bias towards removing the more valuable species during harvesting. In addition, one-third of the consulting foresters attempted to remove at least some of the less valuable species from the stand (species preference ratio ≤0.95), compared to fewer than 20 percent of the industry foresters and nonforesters.

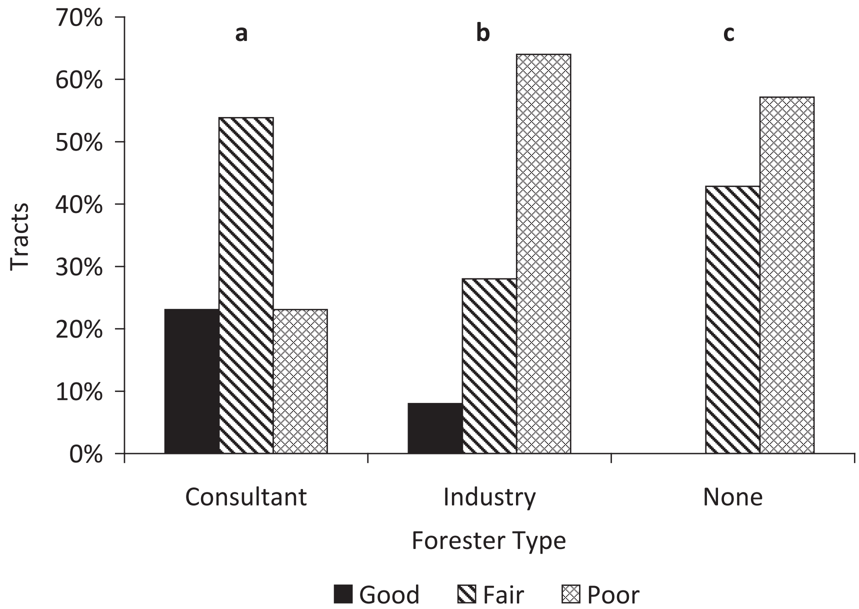

Figure 5.—Harvested NIPF properties in West Virginia classified into overall harvest evaluation classes by type of forester involved with the harvest. Forester type distributions with the same letter are not significantly different based on Pearson's chi-square goodness-of-fit test ($\alpha = 0.10$).

Nearly one-fourth of the harvests conducted by consulting foresters were evaluated as "good" based on evaluations of residual stocking level, acceptable growing stock, and damage to residual trees, as described in Table 1 (Fig. 5). Fewer than 10 percent of the harvests conducted by industry foresters received a "good" evaluation and none of the harvests conducted by nonforesters were rated as "good." About one-fourth of the harvests conducted by consulting foresters were evaluated as "poor," compared to more than 50 percent of nonforester harvests and more than 60 percent of the harvests conducted by industry foresters.

DISCUSSION

Results from this study suggest that there are significant differences between timber harvests conducted by consulting foresters (including state service foresters) and timber harvests either handled by industry foresters or conducted without involvement by any professional forester. By contrast, there were very few differences in the attributes we measured between harvests conducted by industry foresters and harvests carried out by nonforesters.

Consulting foresters removed less volume and value from the stand during harvesting compared to the other two groups and tended to remove trees that were somewhat smaller in diameter, as evidenced by the smaller reduction in QMD after harvesting. In addition, consultants were less inclined to remove the more valuable species from a stand, particularly in the 12- to 15-inch diameter classes, which represent future sawtimber growing stock. Industry foresters and nonforesters removed a very high proportion of high-value species ≥16 inches in diameter, which is consistent with trends observed for timber harvesting in general in West Virginia and eastern Kentucky (Fajvan et al. 1998, Luppold and Bumgardner 2009). Industry foresters and nonforesters strongly avoided harvesting low-value species (e.g., beech and sweet birch), yet consultants tended to harvest these species heavily. In all but one instance, consulting foresters marked the timber to be harvested, compared to only one-quarter of the harvests conducted by industry foresters and less than 10 percent of the harvests conducted by nonforesters. Collectively, these tendencies provide strong evidence that many consulting foresters conducted harvests with the intent to practice silviculture, to at least some extent. In general, such intentions appear to be lacking from most harvests conducted by industry foresters and nonforesters.

Residual stands resulting from harvests managed by consulting foresters were generally in better condition than residual stands resulting from harvests conducted by the other two groups. When consulting foresters conducted the harvest, stands were more likely to be left in a fully stocked condition and have higher proportions of acceptable growing stock and trees in dominant or codominant canopy positions. In addition, consultant-managed harvests resulted in fewer damaged residual trees and fewer trees of the lowest quality (culls and non-sawtimber quality).

It is impossible to determine the initial quality of the timber examined in this study prior to harvest. Therefore, it is impossible to know for certain if differences in residual timber quality are the result of differences in initial stand conditions or differences in the manner in which the harvests were conducted. However, given the size of this study and the randomness with which properties were selected, there is little reason to believe that significant differences in initial timber quality existed between the various forester types. Regardless of whether such differences existed, several factors (damage to residual trees, stocking level, percentage of residual trees in dominant or codominant canopy positions, reduction in QMD) are not influenced by initial timber quality. Ample evidence based solely on these factors supports the claim that consulting foresters conducted harvests with the intent to practice silviculture, to the extent possible given landowner objectives and market constraints.

Residual tree damage was positively correlated with harvest intensity, as measured by the proportion of basal area harvested (Moss 2011). The effect was nevertheless quite small, suggesting that other factors such as terrain, logger skill, logger diligence, and the effectiveness of logging supervision are more important in determining damage to the residual stand. Consulting foresters removed less basal area during harvesting than the other forester groups. However, even accounting for this effect on logging damage, harvests conducted by consulting foresters had less residual tree damage than harvests conducted by either industry foresters or nonforesters.

The overall harvest evaluation was based on three attributes of the residual stand: (1) residual stocking level, (2) percentage of residual basal area in acceptable growing stock, and (3) percentage of residual basal area damaged during logging. These three attributes were chosen because they significantly affect the probability that the stand will be productive and yield high-quality sawtimber in the near future (10 - 20 years). Based on this evaluation method, nearly one-fourth of the harvests managed by consulting foresters were rated as "good." Although somewhat disappointing, this performance is much better than that achieved by industry foresters (less than 10 percent rated as "good") or nonforesters (none rated as "good"). Conversely, more than half of the harvests conducted by industry foresters or nonforesters were rated as "poor" (failing to provide for short-term sustainability). Fewer than 25 percent of consultant-managed harvests were rated as "poor."

A cursory examination of the WVDOF timbering notification forms for 2005 indicated that consulting/service foresters were involved in roughly 20 percent of the timber harvests in West Virginia; industry/procurement foresters were involved in about 30 percent. Approximately half of the timber harvests in 2005 did not appear to include involvement by any professional forester. Assuming that the findings of this study can be applied statewide and forester involvement in harvesting typically follows the pattern shown in 2005, only 7 percent of the timber harvests in the state would receive a "good" evaluation based on the criteria listed in Table 1. Forty-one percent of the harvests would be considered "fair" and more than half (52 percent) would be considered "poor." This outcome is consistent with the findings of other researchers, who have concluded that most timber harvesting in the Appalachian region consists of high-grading and diameter-limit harvests.

Many factors may explain the relatively poor ability of professional foresters to carry out silvicultural harvests. First and foremost are landowner objectives. No attempt was made in this study to ascertain the landowners' objectives for their properties or reasons for harvesting timber. It is likely that some landowners were not interested in silviculture, sustainable timber production, or any of the other aspects of forest management that professional foresters can provide. Given landowners' preferences, there are likely to be instances where non-sustainable harvests are carried out by professional foresters, regardless of their personal preferences towards the harvest.

Additionally, economics dictates how timber harvests are conducted to a considerable extent. Inadequate markets for small-diameter trees, poor quality trees, and certain low-value species seriously hinder foresters' ability to remove such trees from a stand during a commercial harvest, for fear of making the sale economically unattractive. "Textbook" silviculture, including practices such as cleaning and thinning from below, are extremely challenging to perform in the context of a commercial harvest, and few landowners appear inclined to subsidize such activities. Thus, foresters are limited to practicing silviculture within the bounds provided by a commercial (i.e., economically attractive) harvest.

In spite of these constraints, harvest removal attributes and residual stand characteristics suggest that consulting foresters were more apt to integrate silvicultural concepts into their harvests than were either industry foresters or nonforesters (landowners and loggers). This study provided scant evidence that industry foresters were any more likely to practice silviculture as part of a timber harvest than nonforesters.

Part of the reason for the greater likelihood of consulting foresters to conduct silvicultural harvests could lie with the landowners. Landowners who are interested in forest management or concerned about their forest might be more likely to seek out assistance from consulting foresters and state service foresters compared to those landowners with little or no interest in forest management or sustainability. In other words, industry foresters might be just as motivated to practice silvicultural and sustainable harvesting as consulting foresters, but might be more likely to be working with landowners who are not concerned with such matters. Conversely, consulting foresters might be no more likely to practice sustainable forestry than industry foresters when working with unconcerned landowners or landowners whose objectives for their property do not involve forest management. The reader should be aware of the limitations of this study to address such issues and care should be taken in how these results are interpreted.

Nevertheless, one important conclusion from this study is that only a small fraction (probably less than 10 percent) of the timber harvests conducted in the state can be defined as silviculturally oriented. The overwhelming majority of these harvests were carried out by consulting foresters. Landowners should be made aware of the benefits of engaging consulting foresters and state service foresters to assist with their timber sales, particularly if their ownership objectives involve some aspect of forest management.

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EFFICACY AND NONTARGET IMPACT OF MIDSTORY INJECTION IN BOTTOMLAND HARDWOODS

James C. Rainer, Derek K. Alkire, Andrew B. Self, Andrew W. Ezell, Stephen Demarais, and Bronson K. Strickland[1]

ABSTRACT.—Despite the well-documented need for midstory control in bottomland hardwood regeneration, little research has documented the efficacy of such efforts, or the potential negative effects on nontarget stems. More than 72,000 midstory stems located on 90 acres of northern Mississippi bottomland hardwood forest were injected with an imazapyr solution during August 2009. Crown reduction in injected stems was 96.8 percent at 1 year after treatment, with a range of 91.8 to 100 percent by species. Nontarget impact attributed to improper injection technique was observed in one location, but the minor foliar symptoms are not expected to result in long-term damage. No nontarget impacts were observed in other trees on the study site. Residual crop trees did not exhibit negative symptoms from the injection. Injection is effective for controlling midstory stems found in bottomland hardwoods and has a negligible effect on nontarget stems. Midstory injection is often a crucial component of regeneration in bottomland hardwoods and should continue to be used by land managers.

INTRODUCTION

Bottomland hardwood sites are known to have some of the most productive forest soils, and species richness consequently tends to be higher on these sites than on more upland sites (Hodges and Switzer 1979). The high species richness and associated stand stratification often make competition control an essential part of bottomland hardwood regeneration efforts. Midstory injection has long been recognized as a viable and cost-effective method of controlling undesirable stems (Williston et al. 1976). Peairs et al. (2004) reported that midstory/understory control treatment generally increased desirable hardwood regeneration such as oaks (*Quercus* spp). Low light levels often observed in bottomland hardwood stands with dense midstory may not provide sufficient energy for adequate photosynthesis in oak seedlings (Hanson et al. 1987). Lockhart et al. (2000) reported that advanced cherrybark oak (*Q. pagoda* Raf.) seedlings released from midstory competition were 2.5 to 3.4 feet taller than seedlings that were not released.

A variety of chemicals can be used for midstory injection, but many managers use imazapyr (Arsenal® AC) (BASF Specialty Chemicals, Research Triangle Park, NC). Although injection effectiveness can vary by species, tree size, and season of application (Peevy 1971, Star 1973), imazapyr has been proven nearly 100 percent effective on a wide range of species such as black cherry (*Prunus serotina* Ehrh.), blackgum (*Nyssa sylvatica* Marsh.), red maple (*Acer rubrum* L.), American beech (*Fagus grandifolia* Ehrh.), and hickory (*Carya* spp.) (Miller 1993, Nelson et al. 1993).

Potential nontarget impact is a concern for some managers using herbicide treatments in hardwoods. A study in Ohio found that injecting tree-of-heaven (*Ailanthus altissima* Mill.) with a granular form

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of imazapyr (concentration of 83.5 percent) killed all injected trees; however, 17.5 percent of non-injected stems within 3 m were also killed (Lewis and McCarthy 2008). A similar study reported that untreated striped maples (*A. pensylvanicum* L.) were killed on sites where the midstory was injected with imazapyr (Kochenderfer and Kochenderfer 2008). Because interspecific root grafts are rare, Graham and Bormann (1966) concluded the herbicide was absorbed from the soil, which is in agreement with a study in West Virginia (Kochenderfer et al. 2001). The study found that midstory injection with imazapyr was more than 99 percent effective in controlling target midstory stems. Imazapyr treatments also damaged several crop trees, but a very high application rate with 7.5 percent imazapyr concentration may have contributed to the crop tree damage (Kochenderfer et al. 2001). It has been shown that imazapyr exhibits soil activity (Anderson 1996) and can be absorbed by roots of plants (U.S. Forest Service 1989). The half-life of imazapyr in soil ranges from 7 to 180 days in soil and is usually greater than 40 days (Michael and Neary 1991). Therefore, if sufficient quantities of imazapyr reach the soil, the herbicide could affect nontarget stems.

Although some studies have found midstory injection treatments using imazapyr can damage nontarget midstory stems, such as oaks, Ezell et al. (1999) reported that imazapyr had no effect on nontarget overstory stems on injected sites. In light of the conflicting results from previous studies on midstory injection of imazapyr, the objectives of this study were (1) to evaluate the efficacy of imazapyr treatment of midstory stems and (2) to determine if imazapyr affects nontarget midstory and overstory stems in southern bottomland hardwood stands.

STUDY AREA

Location

Six 15-acre study sites typical of southern bottomland hardwood stands along river systems in Mississippi were used in the study. All six areas have similar site characteristics, including species composition, topography, and soil characteristics. The study areas have an overstory with a prominent oak component constituting 67.5 percent of stems. The current overstory contains trees of sawtimber size (diameter at breast height [d.b.h.] ≥11 inches), which account for 87.7 percent of stems. Overstory age distribution among sites ranges from 71 to 97 years, and the average age among sites is 83 years. The overstory basal area ranged from 92 to 122 ft^2 $acre^{-1}$. The midstory in these areas is dominated by shade-tolerant species of limited timber value. A combination of canopy closure and midstory occupancy limits ground cover. Each site predominantly contains soils from the Wilcox association, which are poorly drained soils made up of clay. Soil pH levels ranged between 4.5 and 5.2.

Sites 1 and 2 were located on the John W. Starr Memorial Forest, owned by Mississippi State University. The first of these study sites was located in section 34, T17N R13E in Winston County, Mississippi. The other study site was located in section 15, T17N R13E in Oktibbeha County, Mississippi.

Sites 3 and 4 were located on land owned and operated by C.A. Barge Timberlands LP. The first of these study sites was located in section 12, T15N R14E in Noxubee County, Mississippi. The other study site was located in sections 5 through 8, T15 R16E in Noxubee County.

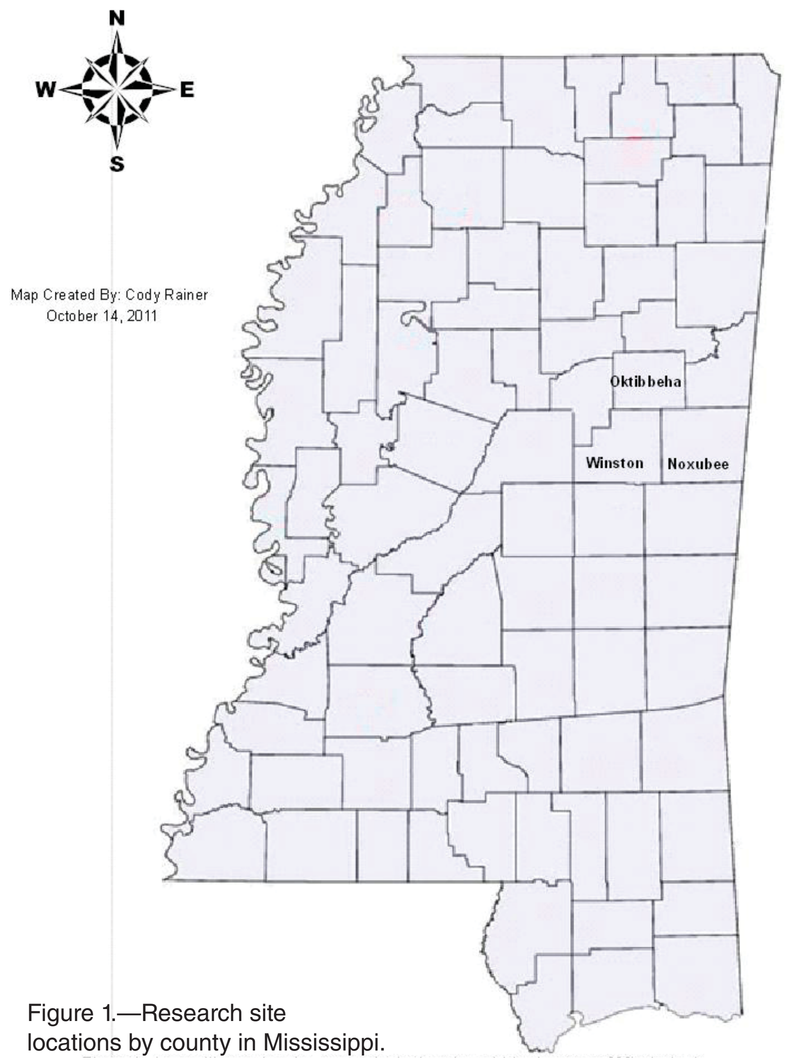

Figure 1.—Research site locations by county in Mississippi.

Sites 5 and 6 were located on the Noxubee National Wildlife Refuge, owned and operated by the U.S. Fish and Wildlife Service. The first of these study sites was located in section 35, T17N R14E in Oktibbeha County. The other study site was located in section 2, T16N, R15E in Noxubee County (Fig. 1).

Stand Composition

Oaks present in the overstory were cherrybark, southern red (*Q. falcata* Michx.), Nuttall (*Q. texana Buckl.*), white (*Q. alba* L.), Shumard (*Q. shumardii* Buckl.), post (*Q. stellata* Wangenh.), water (*Q. nigra* L.), swamp chestnut (*Q. michauxii* Nutt.), overcup (*Q. lyrata* Walt.), and willow (*Q. phellos* L.). There was also a small component of sweetgum (*Liquidambar styraciflua* L.), American beech (*Fagus grandifolia* Ehrh.), black gum, yellow-poplar (*Liriodendron tulipifera* L.), sycamore (*Platanus occidentallis* L.), loblolly pine (*Pinus taeda* L.), baldcypress (*Taxodium distichum var. distichum* [L.] Rich), and hickory (*Carya* spp.) in the overstory of the sites. The midstory contained species such as American hornbeam (*Carpinus caroliniana* Walt.), pawpaw (*Asimina triloba* [L.] Dunal), American holly (*Ilex opaca* Ait.), slippery elm (*Ulmus rubra* Muhl.), red mulberry (*Morus rubra* L.), red maple, sugarberry (*Celtis* l*aevigata* Willd.), eastern hophornbean (*Ostrya virginiana* Mill.), and winged elm (*Ulmus alata* Michx.). This composition is consistent with cover types 91 through 93 documented by the Society of American Foresters.

METHODS

On the six study sites, approximately 72,000 midstory stems were injected by using hatchets and adjustable spray bottles in the "hack and squirt" method. Each non-oak stem in the midstory ≥1 inch in d.b.h. received one hack per 3 inches of d.b.h. with 1 ml of a 20 percent volume-to-volume Arsenal® AC aqueous solution applied per hack. Stems between 1 and 3 inches in diameter received one hack. Midstory injection took place during August and September 2009.

Ninety 0.025-acre plots were evaluated in August 2010 to evaluate the efficacy of the injection. The plots were placed on a systematic grid across each site with 312 feet between each plot. Each midstory stem within a plot was identified by species and diameter and recorded as injected or non-injected. Crown reduction was recorded for all stems using ocular estimation. Evaluation could range from 0 to 100 percent reduction. One individual was responsible for determining crown reduction to maintain consistency throughout the evaluation. Crown reduction as a percentage was also recorded for all overstory stems on the plots. In addition, any damage such as necrosis or chlorosis noted on nontarget stems across the study sites outside the measurement plots was recorded and reported. Recorded data on trees outside measurement plots also included crown reduction, diameter, and species. A 5-acre control was established at each study site to monitor the natural processes of crown reduction in the midstory during the study. Thirty 0.025-acre plots were evaluated within each control.

RESULTS

All sites were uniform in the response to treatments, so we report the results for species and d.b.h. for all sites combined. However, crown reduction was analyzed and is presented individually by site. Overall crown reduction for injected midstory stems on the sample plots was 96.8 percent. Table 1 indicates that injected stems were effectively controlled across all six sites 1 year after treatment. Crown size was reduced by at least 91 percent for all species on all sites (Table 2).

Table 1.—Mean crown reduction of injected stems at each site in Mississippi 1 year after treatment

Site	Mean crown reduction of injected stems (%)
1	94.9
2	96.5
3	96.4
4	96.7
5	96.1
6	97.3
Overall	96.3

Results demonstrated that injection efficacy was excellent on stems with a d.b.h. ≤ 6 inches. Because of the lack of larger-diameter trees in the midstory, sample size for trees with diameters 7 to 11 inches was very low (6, 1, 1, 0, and 1, respectively). We found that the herbicide will control a 1-inch stem or an 11-inch stem as long as a consistent dosage (ml per inch of d.b.h.) is applied. Nontarget midstory stem impact from the injection proved to be minor. Injected midstory stems exhibited 96.8 percent crown reduction, whereas non-injected stems averaged only 0.7 percent crown reduction. Midstory stems in control (untreated) areas had crown reduction similar to non-injected stems in the treatment area.

Table 2.—Mean crown reduction by species of injected stems across all six study sites in Mississippi, 1 year after treatment

Species	Reduction (%)	N†
American hornbeam	100.0	302
Blackgum	99.8	21‡
Deciduous holly	98.0	61
Green ash	97.3	64
Hickory	95.2	470
Pawpaw	99.8	45
Persimmon	97.5	2‡
Red maple	92.3	108
Sweetgum	98.5	94
Winged elm	91.8	214

† Number of stems in sample plots
‡ Insufficient number of stems for valid evaluation

DISCUSSION

Nontarget overstory stems evaluated on all sites exhibited little effect from the chemical injection. Only three overstory stems on the 90 acres injected were observed to be adversely affected. All three stems were sweetgum, which are highly susceptible to imazapyr and reproduce by root suckers. The three stems all exhibited minor symptoms and are expected to have no lasting effects. The adverse impact on the nontarget overstory stems likely can be attributed to the inexperience of one member of the injection crew. The damage occurred in an area where that individual was repeatedly cautioned about poor injection technique.

It is also possible that these sweetgum trees shared a common root system with injected stems. Root suckering is rare in southern hardwood species, and none of the more valuable and highly desirable species exhibit this trait. Sweetgum and American beech are the species most often associated with this feature, but it is important to note that the high density of midstory stems where the damaged trees were located also characterized numerous other areas in the study. Yet in all the areas examined during the sampling and in a more extensive survey to check for nontarget impact, we did not find similar damage.

We think the lack of consistent nontarget impact considered in conjunction with the poor injection work of one crew member is appreciable evidence that the symptoms were attributable to "operator error" and not to chemical movement through the root systems. Based on these observations, we can surmise that chemical root transfer is minimal to nonexistent and the crown reduction observed and recorded was due to the natural senescence or dieback common in midstory and understory stems. Any nontarget stem herbicide impact in this study (if any occurred) likely resulted from failure to properly apply the herbicide solution and keep it in the injection frill, which could allow imazapyr to reach the soil and cause nontarget impacts.

CONCLUSIONS

Midstory injection of an imazapyr solution is very effective in controlling target stems. Injected stems in this study were reduced by more than 96 percent. Even though 100 percent crown reduction was not achieved for all injected trees 1 year after treatment, trees with crowns severely damaged by herbicide died by the next growing season. Nontarget impact of injection was almost nonexistent and was represented by only minor symptoms. The lack of consistent nontarget impact suggests that root grafting was not a principal factor in any chemical movements. Nontarget stems negatively affected may be attributed to an inexperienced injection crew.

Imazapyr is not the only herbicide used for injection which exhibits soil activity. Although this study is the first one in which we have formally evaluated plots for nontarget impact, we have injected hundreds of acres of hardwoods with imazapyr solutions and have never found any nontarget impact to our desirable crop trees. In this study, there were many midstory sweetgum stems in dense areas which were missed during injection. These stems were the best candidates to exhibit symptoms resulting from root graft transfer, yet none did. Conducted properly, injection with imazapyr requires substantially less labor than conventional injection (most trees receive only one hack) and is a very cost-effective tool for controlling undesirable stems in southern bottomland hardwoods.

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MIDSTORY HARDWOOD SPECIES RESPOND DIFFERENTLY TO CHAINSAW GIRDLE METHOD AND HERBICIDE TREATMENT

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Abstract.—Foresters in the Central Hardwoods Region commonly fell or girdle interfering trees and apply herbicide to the cut surface when performing intermediate silvicultural treatments. The objective of this study was to compare the use of single and double chainsaw girdle methods in combination with a herbicide treatment and, within the double girdle method, compare herbicide placement in upper, lower, or both cuts. Triclopyr amine (Garlon® 3A) was applied to girdle cuts to blackgum (*Nyssa sylvatica* Marsh.), hickory (*Carya* spp.), and sugar maple (*Acer saccharum* Marsh.) trees. After three growing seasons, sugar maple was killed by all methods tested, with the single girdle without herbicide treatment recommended as the most cost-effective method of control. In hickory, all girdle treatments, with or without herbicide, resulted in almost complete top kill. However, the single girdle produced higher sprout frequency (50%) and lower tree mortality (40%) than other treatments. Blackgum was difficult to kill with any treatment. Girdle treatments using herbicide top killed from 89 to 95 percent of blackgum stems; those not using herbicide killed only 21 to 29 percent. Most treated blackgum bole- or root-sprouted regardless of treatment, with herbicide treatments resulting in slightly lower numbers of trees sprouting. Placement of herbicide within the double girdle treatments had no impacts on mortality or sprouting for any species. These results allow foresters to refine their timber stand improvement methods to save herbicide and labor cost.

INTRODUCTION

Many silvicultural treatments, such as preharvest treatments for promoting desirable advance regeneration, post-harvest timber stand improvement (TSI), and site preparation in regeneration openings, call for the removal of undesirable, interfering trees. Foresters employ several methods for controlling interfering trees including stem injection (hack-n-squirt, frill), basal bark, and chainsaw felling and girdling. Chainsaw girdling usually involves a single, continuous cut around the entire circumference of the stem at a height between 3 and 4 feet from the ground, followed by the application of a herbicide to the cut surface. Where herbicide use is excluded, TSI contracts often require two girdles approximately 6 to 12 inches apart. Double girdling may also be done in stands where certain species, like yellow-poplar (*Liriodendron tulipifera* L.), may be sensitive to herbicide "flashback." Flashback is believed to occur when an untreated tree takes in herbicide through shared root grafts from a neighboring treated tree of the same species and consequently suffers herbicide damage (Rathfon et al. 2009).

Noel (1970) provides an extensive review of early literature addressing the physiological effects of girdling on trees, but most of the studies he cited involved the use of axes or other non-motorized means of girdling and few involved the use of herbicides. For example, Clark and Liming (1953) reported that early summer girdling of blackjack oak (*Quercus marilandica* Münchh.) in the Missouri

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Ozarks resulted in the fewest number of basal sprouts compared to girdling done at other seasons. They also found that shallow girdles ("peels") that severed only the phloem and cambium but did not cut into the xylem resulted in less sprouting than "notch" girdling, which did cut into the xylem. Perkey et al. (1994) observed that tree species with ring-porous xylem appeared to be more quickly top killed following chainsaw girdling than species with diffuse-porous xylem.

Olson and Boggess (1960) observed that sprouting of hardwoods girdled in Illinois decreased with increasing tree diameter. Some northern hardwoods axe girdled in New Hampshire died within 1 year; most were dead within 4 years (Baldwin 1934). Cut surface herbicide treatments such as girdle, frill, and cut-stump usually perform better when applied during the growing season (Ballard and Nowak 2006, Greth 1957). Midwinter and early spring treatments often result in lower reported mortality. One reason may be heavy sap flow flushing herbicide from the wound. Root reserves during the dormant season are also usually sufficient for most species to at least temporarily maintain crown survival following girdling treatments. For this reason, dormant-season control treatments most often result in greater frequency and abundance of stump and root sprouting in hardwoods when compared to other treatment timings (Kays and Canham 1991).

Although foresters have much collective experience with what treatments are effective and which tree species are difficult to control, few results of controlled experimentation on the chainsaw girdle method in combination with herbicide treatment have been published. The objectives of this experiment were to: (1) test the use of single and double chainsaw girdle methods in combination with an herbicide treatment for the control of several common interfering tree species during intermediate stand treatments and site preparation in Central Hardwoods forests; and (2) within the double girdle method, determine the most effective placement of herbicide, i.e., applied to the lower girdle, upper girdle, or to both.

METHODS

The study was conducted in a 33-acre mature oak-hickory stand on Ferdinand State Forest in Perry County in the nonglaciated region of south-central Indiana. The study was conducted in conjunction with post-harvest TSI following a single-tree selection commercial thinning that removed 2,400 board feet (Doyle) per acre. The overstory forest was composed primarily of oak (*Quercus* spp.) and hickory (*Carya* spp.), which accounted for 70 percent of the total preharvest stocking. A midstory canopy was dominated by sugar maple (*Acer saccharum* Marsh.), blackgum (*Nyssa sylvatica* Marsh.) and a mix of other shade-tolerant species. Pignut (*C. glabra* [Mill.] Sweet) and shagbark (*C. ovata* [Mill.] K. Koch) hickories were prominent in the intermediate and overtopped crown classes. The timber harvest occurred in winter 2006. Cull tree removal, crop tree release, and midstory removal were conducted over 3 days from February 2 through February 16, 2007. High temperatures ranged from 19 to 43 ºF, averaging 31 ºF, with sunny to partly sunny conditions. Sugar maple sap flow on cut stems ranged from none to heavy; and most stems produced at least some sap flow. Although midwinter TSI is not the optimal time for control of many hardwood species, foresters often prefer this period to growing-season TSI operations to avoid excessive heat, humidity, and pests.

Six treatments were applied randomly to individual trees. They were:

1) Single girdle
2) Single girdle + herbicide
3) Double girdle
4) Double girdle + herbicide delivered to lower cut
5) Double girdle + herbicide delivered to upper cut
6) Double girdle + herbicide delivered to both cuts

Girdles were made to a depth of approximately 0.25 to 0.5 inches into the sapwood using a Stihl 200T® (Stihl Inc., Virginia Beach, VA) professional arbor saw with a 14-inch bar and 3/8-inch pitch and 0.05-inch gauge Stihl Picco® chain. Herbicide was triclopyr amine (Garlon® 3A) (Dow AgroSciences, Indianapolis, IN), diluted at 1:1 ratio (22.2 percent active ingredient) with water, applied to the cut surface with one of the ordinary garden, hand-pump, 1-quart spray bottles most commonly used by foresters for TSI work in the Central Hardwoods Region.

Because this was an operational TSI job, there was some variation in the numbers of trees receiving each treatment. Although 10 species were treated, only blackgum, hickory, and sugar maple were present in large enough numbers to include in the analysis. A total of 453 stems were treated, with blackgum, hickory, and sugar maple comprising 183, 92, and 139 stems, respectively. Stem diameter at breast height (4.5 ft; d.b.h.) of treated trees ranged from 4 to 14 inches with a mean of 7.4 and standard deviation 1.85. Sugar maple stems were smaller (6.7 inches mean d.b.h.) whereas the blackgum and hickory stems were comparable in size to one another (7.7 and 7.8 inches mean d.b.h., respectively).

Treatment results were observed for individual trees at five different times over the three growing seasons following treatment application: June and October 2007, June and October 2008, and September 2009. Stem mortality (SM) or top kill, defined as death of the aboveground portion of the tree, was observed and recorded as alive or dead. Stump, bole, and root sprouting frequency (SP) were reported as having sprouts or not having sprouts. Tree mortality (TM), defined as trees completely dead, both above and below ground, was determined for each stem by whether the tree experienced stem mortality and whether it had living sprouts. TM was recorded as alive or dead for each treated tree.

Two separate lines of analysis were performed to address the objectives of the study. To test the combinations of girdle type and herbicide application for objective 1, data included only responses to treatments 1 to 3 plus the sum of responses to treatments 4, 5, and 6 (i.e., double girdle + herbicide). To test the placement of herbicide in the double girdle treatment for objective 2, data included only responses to treatments 4 to 6. For both analyses, chi-square contingency tables of the count data were used to determine overall independence of the response variables, namely SM, SP and TM, from September 2009, from girdle or herbicide placement treatments. Separate tests were conducted for each species. If the null hypothesis was rejected ($\alpha = 0.05$), multiple comparison chi-square tests were calculated to test for differences between individual treatments. A Bonferroni adjustment was made to determine significant differences in these multiple comparison tests, with significant differences occurring at $P < \alpha/t$, where t = total number of comparisons.

Table 1.—Stem mortality, tree mortality, and sprouting frequency 3 years following chainsaw girdle treatments with and without herbicide applied to the girdle cut(s) for several Central Hardwoods tree species†

Species	Treatment					
	Single girdle	Single girdle + herbicide	Double girdle	Double girdle + herbicide	χ^2	*P*
	-------------------- Stem mortality (%) ------------------					
Blackgum	21 b ‡	95 a	29 b	89 a	78.02	<0.001
Hickory spp.	90	100	100	100	7.30	0.063
Sugar maple	100	100	97	100	1.82	0.611
	-------------------- Tree mortality (%) -------------------					
Blackgum	17	24	8	26	5.57	0.134
Hickory spp.	40 b	81 ab	71 ab	91 a	13.54	0.004
Sugar maple	100	100	97	100	1.82	0.611
	--------------- Sprouting frequency (%) ---------------					
Blackgum	83	71	92	73	7.12	0.068
Hickory spp.	50 b	19 ab	29 ab	9 a	9.73	0.021
Sugar maple	0	0	0	0	0.00	1.000

† Chi-square contingency analysis was performed on stem count data (not shown) to test for overall differences between treatments within each species group (χ^2 and P). Species groups with significant differences at α = 0.05 were further tested with a chi-square multiple comparison on the count data using the Bonferroni adjustment.

‡ Treatments with the same letter were not significantly different from one another when P > 0.05/t, where the number of comparisons (t) = 6.

RESULTS

Girdle Method

With the exception of the double girdle treatment, all sugar maple trees were dead with no sprouts within 3 years, regardless of the treatment (Table 1). Only 1 out of 39 sugar maple trees treated with the double girdle survived. All girdle treatments resulted in almost complete SM in hickory. The exception was the single girdle, which resulted in 1 out of 10 stems surviving (90% SM). The single girdle produced higher SP (50%) and lower TM (40%) than all other treatments applied to hickory. Where herbicide was applied to both the single girdle and the double girdle, SM in blackgum was greater than their non-herbicide counterparts. Thirty-six of 38 (95%) and 65 of 73 (89%) blackgum stems were dead following treatment with single girdle + herbicide and double girdle + herbicide treatments, respectively. Only 11 of 38 (29%) and 5 of 24 (21%) blackgum stems were dead following double girdle and single girdle treatments, respectively. SP was high and ranged from 27 of 38 (71%) in the single girdle + herbicide treatment to 35 of 38 (92%) in the double girdle treatment. TM was low, ranging from 3 of 38 (8%) in the double girdle treatment to 19 of 73 (26%) in the double girdle + herbicide treatment. None of the SP or TM treatment differences in blackgum was considered significant, however.

Table 2.—Stem mortality, tree mortality and sprouting frequency 3 years following double chainsaw girdle treatments with herbicide applied to lower, upper, or both girdle cuts for several Central Hardwoods tree species[†]

	Herbicide placement				
Species	Lower cut	Upper cut	Both cuts	χ^2	*P*
	----------- Stem mortality (%) ----------				
Blackgum	74 b [‡]	95 ab	100 a	9.33	0.025
Hickory spp.	100	100	100	0.00	1.000
Sugar maple	100	100	100	0.00	1.000
	----------- Tree mortality (%) ----------				
Blackgum	19	24	36	3.33	0.344
Hickory spp.	73	100	100	7.41	0.060
Sugar maple	100	100	100	0.00	1.000
	------ Sprouting frequency (%) -------				
Blackgum	78	76	64	2.42	0.489
Hickory spp.	27	0	0	7.41	0.060
Sugar maple	0	0	0	0.00	1.000

[†] Chi-square contingency analysis was performed on stem count data (not shown) to test for overall differences between treatments within each species group (χ^2 and P). Species groups with significant differences at $\alpha = 0.05$ were further tested with a chi-square multiple comparison on the count data using the Bonferroni adjustment.

[‡] Treatments with the same letter were not significantly different from one another when $P > 0.05/t$, where the number of comparisons (t) = 3.

Herbicide Placement within Double Girdle

All sugar maple trees were dead with no live sprouts 3 years following double girdle treatment, regardless of which girdle cut herbicide was applied to or whether it was applied to both cuts (Table 2). Double girdle treatment with herbicide, regardless of herbicide placement, controlled 100 percent of hickory stems. Placing herbicide in the lower girdle cut of hickory seemed to reduce TM and increase SP from the 100 percent mortality and no sprouts of the other two herbicide placements. Those differences were not significant (p = 0.060) (Table 2), however. There were, however, differences in SM among placement treatments for blackgum (p = 0.025) (Table 2). Applying herbicide to the lower girdle cut controlled 20 of 27 (74%) blackgum stems. Applying herbicide to the upper girdle cut or to both girdle cuts controlled 20 of 21 (95%) and 25 of 25 blackgum stems, respectively. TM for blackgum ranged from 5 of 27 (19%) where herbicide was applied to the lower cut, to 9 of 25 (36%) where herbicide was applied to both cuts. SP ranged from 21 of 27 (78%) where herbicide was applied to the lower cut, to 16 of 25 (64%) where herbicide was applied to both cuts. None of the TM and SP treatment differences in blackgum was significant.

DISCUSSION

The choice of whether to use a single or double chainsaw girdle and herbicide depends on tree species being treated, silvicultural objectives for the stand, and timing of application. In intermediate stand treatments such as thinning and crop tree release, particularly in stands beyond the sapling stage of stand development, tree mortality of the competitors is not essential to the release of the crop trees as long as competitors die back long enough to allow the crop tree to fully capture the growing space. Sprouting in these treatments may occur with little chance of those sprouts regaining a position in the stand canopy. On the other hand, controlling sprouting is critical for site preparation in regeneration openings and silvicultural clearcuts or where desirable advance reproduction is developing in a shelterwood.

In oak shelterwoods in southern Indiana where sugar maple dominated the midstory canopies, complete tree mortality was achieved within 16 months of a midsummer treatment by using a single chainsaw girdle with Pathway® (Dow AgroSciences) herbicide (5.4 percent picloram + 20.9 percent 2,4D) (Rathfon 2011). In this study, sugar maples from 5 to 11 inches in d.b.h. were readily killed within 3 years by using a single girdle with no herbicide applied. Therefore, regardless of silvicultural objectives, a single girdle will suffice in controlling unwanted sugar maple. Herbicide is unnecessary and often wasted if applied midwinter due to sugar maple's heavy sap flow. Although all treatments in this study resulted in some level of sprouting in sugar maple in the first growing season after treatment, no live sprouts remained by September 2009, the end of the third growing season.

Sugar maple can reproduce through stump sprouts of trees that have been broken or cut off (Godman et al. 1990). Sprouting frequency decreases as tree size increases (Solomon and Blum 1967). Perala (1974) observed that 85 percent of sugar maple from 10 to 14 inches in d.b.h, stem killed by a prescribed fire, had sprouts 5 years later. This stem killing would be similar to that resulting from girdling. However, Olson and Boggess (1960) found that 93 percent of girdled sugar maple in southern Illinois were top killed whereas only 19 percent sprouted. Sugar maple tends to sprout less vigorously in the southern part of its range (Godman et al. 1990). Sugar maple sprout survival may also depend on light levels at the forest floor. Although sugar maple is shade tolerant, its sprouts may require more sunlight than occurred in this study following the single-tree selection harvest and TSI.

Although hickory was easy to top kill, herbicide was needed to achieve greater than 70-percent TM. Even when herbicide was used in a single girdle, only 81 percent of treated trees died with no sprouts. In hickory trees girdled in southern Illinois, 89 percent were top killed and 43 percent produced sprouts (Olson and Boggess 1960). A double girdle with herbicide placed in the upper cut or both cuts was required to assure 100-percent mortality with no live sprouts. The double girdle with herbicide placed in the lower cut performed no better than the double girdle with no herbicide. This lack of sprout control along with the complete control produced by the double girdle with herbicide placed in the upper girdle seems counterintuitive. Herbicide placed in the lower girdle might be expected to be more readily transported via the phloem to the roots. If the herbicide is placed in the upper girdle where the phloem below it is cut off, the transport of herbicide to the roots would presumably be cut off (Hess 1995). Nonetheless, when greater than 8-percent tree mortality is desired when controlling hickory, these results show that double girdling with herbicide placed in the upper girdle is sufficient to that end.

As easy as sugar maple was to kill, blackgum was difficult to kill. MacKinney and Korstian (1932) found that black gum was the species most resistant to non-chemical ax girdling and to herbicidal frilling treatments among 21 species treated in the Appalachian Mountains of North Carolina. Blackgum not only has the ability to produce vigorous stump sprouts, but it also sprouts prolifically from its roots (McGee 1990). In southern Illinois, 67 percent of girdled blackgum were top killed and 74 percent sprouted (Olson and Boggess 1960). By most forest management standards, herbicide is necessary for the control of blackgum regardless of silvicultural objectives and stand development.

Double girdling did not improve stem kill over the single girdle without the use of herbicide. Whereas a double girdle with herbicide applied to both cuts produced 100-percent stem kill (Table 2), a single girdle with herbicide provided nearly the same result (Table 1) for half the cost. Double girdling with herbicide provided no advantage over single girdling with herbicide in preventing sprouting or obtaining tree mortality.

The high rate of sprouting and low tree mortality rate for the best treatments does not pose a serious problem in intermediate stand treatments. When the objective is to promote desirable regeneration where a substantial number of blackgum are present, alternative methods for controlling blackgum, such as injection or basal bark, may prove more effective and timely. Growing-season treatments may also prove more effective than dormant season treatments (Ballard and Nowak 2006, Kays and Canham 1991, Kossuth et al. 1978, Zedaker et al. 1987). Ultimately all the treatments will result in the majority of blackgum stems dying. On virtually all girdled blackgum stems not experiencing stem mortality, the trunk below the girdle appeared dead and was decaying, while above the girdle the trunk appeared normal. Eventually decay will advance enough to cause the stem to collapse. For most stems this process apparently takes at least 3 years.

Treatment cost data were not collected in this study. Rathfon (2011) found that an experienced operator performing the single chainsaw girdle method with application of herbicide using the type of spray applicator used in this study, treated 8.4 ft^2 of basal area per hour, compared to 10.7 ft^2 per hour for both a spaced injection treatment (approximately one cut per inch stem d.b.h.) and a basal bark treatment. With herbicide and saw costs included and a labor rate of $25 per hour, the single chainsaw girdle with herbicide treatment cost $3.64 per ft^2 of basal area treated versus $3.61 per ft^2 for the injection treatment and $7.09 per ft^2 for the basal bark treatment.

CONCLUSIONS

Foresters and landowners can save time and money optimizing tree control methods according to species being controlled and stand objectives when performing TSI, intermediate stand treatments, and site preparation in Central Hardwoods forests. For pole- to small sawtimber-sized individuals, a single chainsaw girdle, applied during the dormant season, is sufficient to kill all sugar maple and most hickory in southern Indiana. Nearly complete control of hickory can be achieved by use of a double girdle with herbicide applied to the upper cut. However, chainsaw girdling applied during the dormant season, either with or without herbicide, will not provide complete control of blackgum. The most cost-effective option for stem control of blackgum among those tested in this study is a single girdle with herbicide. A different herbicide, different treatment timing, or both may provide better control of blackgum sprouts.

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The content of this paper reflects the views of the authors(s), who are responsible for the facts and accuracy of the information presented herein.

SEEDLING RESPONSE TO INITIAL OAK WOODLAND RESTORATION TREATMENTS ON THE OZARK NATIONAL FOREST

Jamie L. Schuler, Don C. Bragg, Eric Heitzman, and Jason Milks[1]

Abstract.—Over the last century, the range of oak woodland ecosystems has diminished as woodlands have become more closed-canopy forests. A century of fire suppression efforts has all but eliminated the frequent ground fires necessary to maintain the open canopy characteristics of oak woodland ecosystems. Restoration efforts are underway to return some of the closed-canopy forests to a more open woodland condition. A combination of two prescribed burns followed by a noncommercial thinning treatment (largely thin-to-waste) was used on three sites in the Boston Mountains of Arkansas within the Ozark National Forest between 1999 and 2003. The development of regeneration was assessed 3 years following the thinning treatment. Relative to untreated control sites, the restoration treatment greatly enhanced the development of reproduction. Total stem density was greatest on the upper slope positions of treated sites. Oak reproduction was greatest on the upper slopes on both treated and control sites. For all species combined and oak-only reproduction, the density of stems ≥4 feet was much greater on treated sites. The rapid response of reproduction to the combined burning and thinning treatment will necessitate continued prescribed burning to maintain the open-canopy structural characteristics of oak woodlands. Almost 350 stems acre^{-1} of oak species are present in the ≥4-foot size class, which is likely adequate to maintain an oak presence in these ecosystems.

INTRODUCTION

Oak woodlands represent a transitional community between prairie and forest. Woodlands are characterized as having fewer and more widely spaced trees than forests and a diverse understory of prairie grasses and forbs that are typically maintained by frequent burning (Nuzzo 1986, Taft 1997). Only a small fraction of the original oak woodland areas remains in the United States (Nuzzo 1986) due to changes in historic fire regimes (Abrams 1992). Changes in the historic fire regime and the vegetation structure have caused shifts in plant communities and reduced species diversity. Increases in fire-intolerant plant species, higher stem densities on droughty soils, and the loss of plant and animal species associated with more open plant communities have raised concerns about ecosystem resiliency as well (Ozark-St. Francis National Forest [OSFNF] 2011).

All of the Arkansas Ozarks, and most of what is now the Ozark-St. Francis National Forest, overlap the historical range of oak woodlands. Foti (2004) used information derived from General Land Office notes from the early 1800s to the mid-1800s to describe the forest structure from the Lower Boston Mountains in west-central Arkansas to the Ozark Highlands Plateau, which stretches into

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southern Missouri. He concluded that closed-canopy forests in this region covered only 22 to 38 percent of the landscape (Foti 2004), with overstories generally dominated by red and white oaks (*Quercus* spp.).

The relative openness of these forests was shaped by ground fires that were a common occurrence in this region. Using fire history information pieced together from areas within the southern Ozarks, several sources indicate periods before the early 1900s when fire hot enough to scar trees occurred every 1 to 8 years (Guyette and Spetich 2003, Jurney and Stahle 2004). Forests that developed since this period now have structural characteristics very different from the original woodlands described by early settlers and surveyors. The landscape is now characterized by steep, densely forested hills of oak and hickory (*Carya* spp.), interspersed with shortleaf pine (*Pinus echinata* Mill.) (Anderson et al. 2003). Fire exclusion in the Boston Mountains during the 20th century has also contributed to the development of a dense understory and midstory of shade-tolerant, fire-intolerant tree species (Beilman and Brenner 1951, Penfound 1962).

Lack of a frequent-fire regime coupled with a dense multi-tiered canopy is not conducive to the sustained recruitment of oak seedlings (Franklin et al. 2003, Loftis 2004, Van Lear 2004). In fact, these conditions have contributed to reduced oak regeneration in the region.[2] Additionally, oak decline has had a profound influence on the OSFNF (Heitzman 2003) and has caused significant mortality to mature oak. Together, infrequent fires, the decline of the oak overstory, and an aggrading non-oak understory have created a great deal of uncertainty for maintaining oak woodland ecosystems across the landscape.

One of the challenges to managing oak woodland ecosystems is the lack of management targets for the understory vegetation. For example, little information is available to specify desired woody stem densities, although some have suggested from 10 to 50 percent total cover (e.g., Nelson 2005) for oak woodlands/savannas. Currently, the generalized desired conditions for woodlands are: 60 feet^2 acre^{-1} overstory basal area with >70 percent as oak or oak-pine, 50 percent of overstory trees ≥14 inches in diameter at breast height (d.b.h.), <150 stems acre^{-1} in trees ≥2 inches, >50 stems acre^{-1} as oak or oak-pine (2 to 7 inches in d.b.h.), shrub cover less than 30 percent, and ground layer cover >8 percent (Ozark-St. Francis National Forest 2011).

To address these concerns the OSFNF implemented a large-scale program designed to restore oak woodland structural characteristics by using density reduction treatments and frequent prescribed burning. This paper reports on the hardwood regeneration responses 3 years following the thinning treatment relative to adjacent, undisturbed portions of the OSFNF.

[2]Ozark-St. Francis National Forest, Bayou Ranger District. 2001. Restoring forest ecosystem health in the wildland/urban interface on the Bayou Ranger District: implementing the OSFNF land and resource management plan with the federal wildland fire management policy and program review. Unpublished paper. 21 p. On file with Ozark-St. Francis National Forest, Bayou Ranger District, 12000 SR 27, Hector, AR 72843.

Table 1.—Description of study sites and treatments

Study sites	County	Acreage	Years burned	Year thinned
Treated				
Mulberry Mountain	Pope	185	2000, 2003	2003
Lick Hollow	Pope	494	1999, 2002	2003
County Line	Searcy	125	2000, 2003	2003
Control				
Raspberry Mountain	Pope	119	N/A	N/A
Sulphur Creek	Pope	74	N/A	N/A
Falling Water	Newton	205	N/A	N/A

Table 2.—Average stand density and basal area of stems ≥2.5 inches in d.b.h. for untreated control sites in the Boston Mountains of Arkansas, 2004

Species	Stems ac^{-1}	Basal area (ft^2 ac^{-1})
Hickory (*Carya* spp.)	106	17
White oaks (*Q. alba, Q. stellata*)	111	49
Blackgum (*Nyssa sylvatica*)	27	5
Red maple (*A. rubrum*)	23	2
Shortleaf pine (*P. echinata*)	8	6
Red oaks (*Q. rubra, Q. velutina*)	14	11
Miscellaneous	32	4
Total	322	94

STUDY AREA

Six study sites in the Boston Mountains of Arkansas were chosen (Table 1). Five were located on the Bayou Ranger District and one was located on the Buffalo Ranger District of ONF. All six sites were dominated by south- to west-facing aspects, less than 25 percent slope, and stony and gravelly silt loam soils in the Nella-Enders-Mountainberg associations (Typic Paleudults, Typic Hapludults, and Lithic Hapludults) (Vodrazka et al. 1981). Study site elevations ranged from 1,425 to 2,165 feet above sea level.

Three sites were chosen as treated areas, and three were chosen as control areas. The treated sites (Mulberry Mountain, Lick Hollow, and County Line) were located in Pope and Searcy Counties, Arkansas. Each treated site was burned twice between 1999 and 2003, and thinned in summer 2003. Control sites (Raspberry Mountain, Sulphur Creek, and Falling Water) were chosen from stands within 15 miles of treated sites and had no history of cutting or burning in at least 80 years. No pretreatment measurements were taken on any of the sites. However, the control sites, which were selected for their similarities to the treated sites in soils, aspect, slope, size, and species assemblage, averaged 94 $feet^2$ $acre^{-1}$ and 333 stems $acre^{-1}$ for stems ≥2.5 inches in d.b.h. 1 year following the thinning treatments (Table 2). Dominant species were various hickories, white oaks (including post oak [*Q. stellata* Wangenh.]), and red oaks (both northern red [*Q. rubra* L.] and black oak [*Q. velutina* Lam.]).

METHODS

For the treated sites, all burns were conducted during the dormant season (February through early March). Fires were ignited by using grid-pattern aerial ignition and backing fire with hand ignition from established fire lines. The burned sites were subsequently thinned with chainsaws to 30-50 $feet^2$ $acre^{-1}$. Felled trees were left in the woods and used for public firewood collection (see Milks 2005 for a more detailed description).

Ten 0.10-acre overstory plots were systematically established along an elevational gradient on each of three slope positions per site: upper slope, middle slope, and lower slope (30 plots per site). Across all sites, the mean difference in elevation between upper and lower slope transects was 353 feet. Transect lengths varied from about 490 to 3,280 feet, depending on the size and shape of the site. Plots were equally spaced along each transect.

Three 0.001-acre circular plots were located 25 feet from each overstory plot center at 120º intervals (i.e., 30 plots per slope position) to quantify understory vegetation. All woody stems taller than 1 foot and less than 1.0 inch in d.b.h. were tallied by species, height class, and stem origin (sprout or nonsprout). Height classes were defined as 1.0 to 1.9 feet tall (class 1), 2.0 to 2.9 feet tall (class 2), 3.0 to 3.9 feet tall (class 3), and 4.0 feet tall and above (class 4).

DATA ANALYSIS

Hardwood regeneration was analyzed as a split plot with whole plots arranged in a completely randomized design by using a SAS version 9.2 mixed model procedure (SAS Institute, Cary, NC). Treatments were defined as the whole plot factor. Slope position (upper, middle, and lower) was considered the subplot factor. Mean seedling density of hardwood regeneration was compared between treated and control sites, and among slope positions. Significance for all tests was evaluated by using alpha = 0.05. A Tukey-Kramer adjustment was used for multiple comparison testing.

RESULTS

Three years following the thinning treatments, average seedling density for all species ranged from 3,578 to 9,044 stems $acre^{-1}$ across treatments and slope positions (Table 3). As expected, treated sites have higher stem densities than nontreated sites ($P = 0.0061$). On control sites, the three slope positions were similar in terms of total stem density, averaging 3,938 stems $acre^{-1}$. On the treated sites, total stem density increased with increasing slope position and averaged more than twice the number of stems relative to control sites (trt*pos interaction, $P = 0.0354$) (Table 3).

For all species combined, the number of stems per height class interacted with treatment ($P < 0.0001$) (Fig. 1). The greatest numbers of seedlings were found in height class 4 on the treated sites. Ninety percent of the seedlings in this largest size class were considered moderately tolerant to tolerant of shade. Red maple (*Acer rubrum*) was the most frequently encountered shade-tolerant species with an occurrence of 28 percent. Additionally, 30 percent of the seedlings in height class 4 were of sprout origin. The vast majority of the seedlings on the control sites were in the smallest height class regardless of slope position.

Table 3.—Mean seedling densities by slope position for sites being restored by using burning and thinning treatments (treated) relative to untreated reference sites in the Boston Mountains of Arkansas, 2006

Treatment	Position	All species† (stems ac^{-1})	All oak species (stems ac^{-1})
Control	Lower	4,544 b	400
Control	Middle	3,578 b	422
Control	Upper	3,608 b	878
Treated	Lower	5,451 ab	294
Treated	Middle	6,378 ab	1,100
Treated	Upper	9,044 a	1,456

†Stem densities under the "all species" heading followed by the same letter are not significantly different at alpha = 0.05. The interaction among treatment and position was not significant for the oak species.

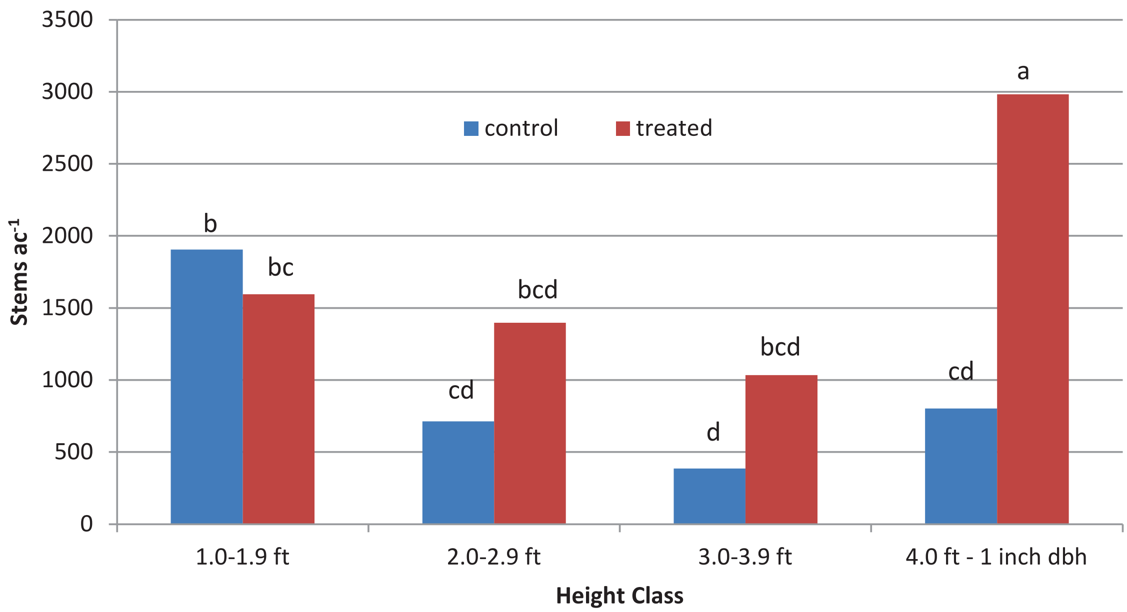

Figure 1.—The distribution of regenerating stems (all species) by height class for sites being restored by using burning and thinning treatments (treated) relative to untreated reference sites in the Boston Mountains of Arkansas. Stem densities were determined 3 years after the thinning treatment was applied. Values followed by the same letter were not significantly different at alpha = 0.05.

Red and white oak stem densities ranged from 294 to 1,456 stems $acre^{-1}$ among treatment and slope position combinations (Table 3), which accounted for up to 17 percent of the total stem density. Treatment effects were not significant (P = 0.1110) whereas slope position influenced stem density (P = 0.0177). On average, more stems were located on high slope positions (1,167 stems $acre^{-1}$) compared to lower slopes (347 stems $acre^{-1}$). Neither position differed from mid-slope positions (761 stems $acre^{-1}$). Oak stem density also varied by height class between the treatments (P = 0.0231, Trt*HC interaction) (Fig. 2). Control sites had fewer stems in the taller height classes; treated sites had high stem densities in the smallest and largest classes. However, this result was not entirely due to increased sprouting. Sprout-origin oak seedlings represented 5, 9, 17, and 11 percent of the total oak seedling density for height classes 1 to 4, respectively.

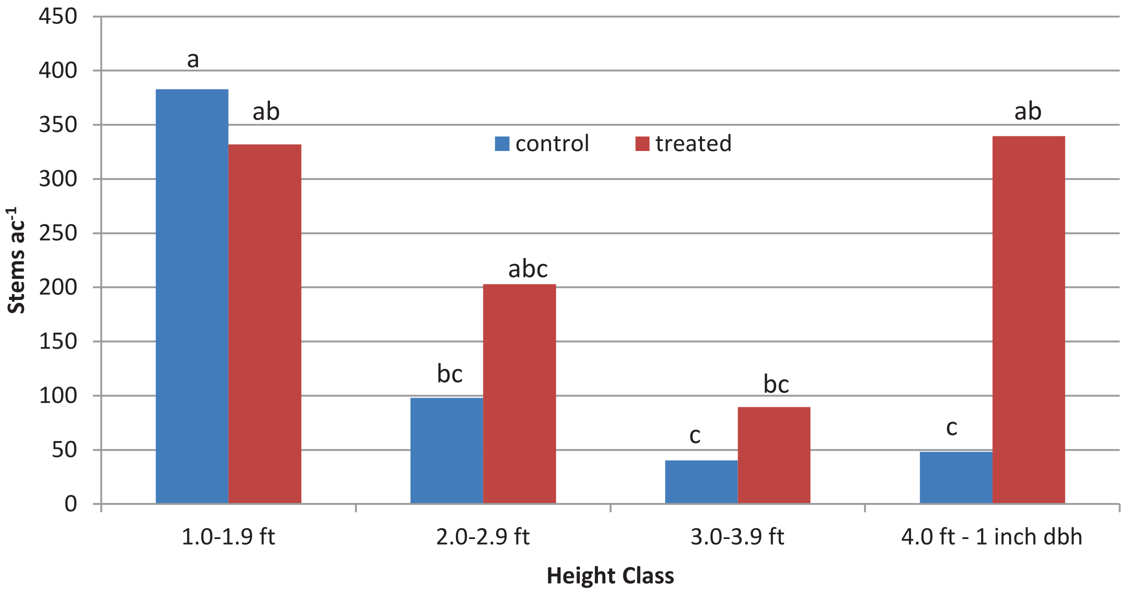

Figure 2.—The distribution of regenerating stems (oak-only) by height class for sites being restored by using burning and thinning treatments (treated) relative to untreated reference sites in the Boston Mountains of Arkansas. Stem densities were determined 3 years after the thinning treatment was applied. Values followed by the same letter were not significantly different at alpha = 0.05.

DISCUSSION

The structural characteristics of oak woodlands have been changing over the last century due to altered disturbance regimes. Sites that historically were characterized as woodlands have now formed closed canopies with midstory and understory layers that are also well established. Burning and thinning treatments as conducted here are a first step in the oak woodland restoration process and have increased understory light levels, reduced competition, and promoted a vigorous seedling response.

Obviously, the manipulation of the overstory to reduce canopy cover was the easiest objective to fulfill. In time, however, some recruitment into the overstory will be necessary for the continued sustainability of these ecosystems. For example, the prescribed burns conducted in this study resulted in about 15 percent wounding and 1.5 percent mortality across all oak stems (Milks 2005). Additional mortality should be expected from lightning, windthrow, and other aboitic and biotic factors. Additional oak stems will be needed to fill these gaps over time.

Although understory woody stem density following burning and thinning was somewhat lower than similar stands regenerated by using shelterwood reproduction methods (Graney and Murphy 1995, Graney and Rogerson 1985), probably due to the two fires prior to thinning, stem densities are more than adequate to meet recruitment objectives. Burning and thinning shifted the distribution of stems among the height classes, and resulted in more stems in the largest height classes, whereas the largest seedling pool on control sites occurred in the smallest height class (Fig. 1). This increase probably resulted from more favorable light conditions and a compensatory response from top-killed seedlings (Kruger and Reich 1993).

The increased available light coupled with a reduction in competition from other seedlings (at least short-term) may give oaks a competitive advantage over the faster-growing shade-tolerant species (Johnson et al. 2009, Loftis 2004, Van Lear 2004). Even though oak seedling numbers were increased on height classes 2 to 4 compared to control sites, height class 4 (≥4 feet tall) had the only significant increase (Fig. 2). Though not documented, this increase is likely an artifact of a wider permissible range of stem sizes (i.e., 4 feet tall to 1.0 inch in d.b.h.) and ingrowth. Sprouting is an especially important mechanism of oak regeneration in the Ozark Mountains (Johnson et al. 2009, Loftis 2004, Van Lear 2004), but relatively low percentages were actually observed. This finding, however, may be related to our ability to detect sprouting on small seedlings.

Regardless of the reason, it appears that enough large oak seedlings (≥4 feet tall) are present (about 350 stems acre^{-1}) to develop into the targeted minimum of 50 stems acre^{-1} in the 2- to 7-inch d.b.h. size class. The next concern will be how to reduce stem densities without jeopardizing the recruitment of these oak seedlings. Without additional disturbances, the remaining woody understory will continue to persist and develop into midstory and overstory positions. The understory may grow 3 to 4 feet over the next 5 years under current stocking levels (Graney and Rogerson 1985). Within another decade, some stems will exceed a threshold where high-intensity fires can top-kill stems (Maslen 1989).

Subsequent prescribed burns should favor the maintenance and recruitment of oaks over fire-intolerant non-oak species that may otherwise outcompete smaller oaks (Blake and Schuette 2000, Johnson et al. 2009, Peterson and Reich 2001). This process increases the probability that some oaks can move into the upper canopy positions (Johnson et al. 2009, Loftis 2004, Van Lear 2004). The repeated burns may also help xerify the site, making it less favorable for establishing mesic hardwoods (Johnson et al. 2009, Loftis 2004).

Other management options include the targeted use of selective and nonselective herbicides to reduce woody stem cover and increase cover of grasses and forbs. For example, a growing-season application of sulfometuron methyl broadcasted over the top of a regenerating upland oak stand resulted in reduced stem densities and depressed height growth on certain non-oak species without affecting any of the oak component (Schuler and Stephens 2010). Additionally, directed applications of systemic herbicides (e.g., glyphosate) can be very effective but limited by the inherent efficiency at which large areas can be treated.

CONCLUSIONS

The burning and thinning treatments appear to be a successful technique to quickly modify mature, closed-canopy upland hardwood forests to more closely mimic the structural characteristics of oak woodlands. Repeated fires or some other intervention will be required to reduce the woody understory to keep the overstory canopies open. After two burns and one thinning, fire-tolerant species (e.g., oak) are increasing in density in the larger height classes, which further typifies the woodland structural characteristics.

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The content of this paper reflects the views of the authors(s), who are responsible for the facts and accuracy of the information presented herein.

ANALYSIS OF TWO PRE-SHELTERWOOD PRESCRIBED FIRES IN A MESIC MIXED-OAK FOREST IN WEST VIRGINIA

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Abstract.—In 2009, a mesic mixed-oak forest in West Virginia treated with two prescribed fires (2002-2003 and 2005) to eliminate a shade-tolerant understory was characterized by 7,500 seedlings/acre ≥1.0 foot tall of oak (*Quercus* spp.), maple (*Acer* spp.), black birch (*Betula lenta*), and yellow-poplar (*Liriodendron tulipifera*) combined. Maple was the most abundant group before burning but thereafter, maple (1,192/acre), oak (1,557/acre), and yellow-poplar (1,597/acre) seedlings ≥1.0 foot were approximately equally represented. Black birch was the single most abundant species (3,337/acre). Following the prescribed fire treatments, sapling density was reduced by about 90 percent and has not recovered. Fire effects to the overstory, canopy, and subsequent understory light environment were not significant, but a shelterwood harvest in 2009-2010 reduced overstory basal area from 145 to 62 feet^2/acre and from 108 to 44 stems/acre (diameter at breast height ≥5.0 inches). A post-shelterwood prescribed fire is planned for 2013 or 2014 and will complete the experimental design of this study.

INTRODUCTION

Many mixed-oak (*Quercus* spp.) forests in the Eastern United States exhibit a trend of declining oak importance (Abrams 1992). This shift is occurring as overstory oaks are harvested or die and then are being replaced by shade-tolerant species present in lower canopy strata (Schuler 2004). In the central Appalachians, species such as red and sugar maple (*Acer rubrum* and *A. saccharum*) and black birch (*Betula lenta*) have become increasingly abundant in stem numbers and growing stock volume over the past several decades (Alderman et al. 2005, Fei and Steiner 2007, Schuler 2004). Nowacki and Abrams (2008) refer to this trend as the “mesophication” of eastern forests and attribute much of the cause to the lack of periodic fire throughout much of the 20th century.

Silvicultural guidelines that have been developed to sustain oak and reverse the mesophication trend include various herbicide applications, prescribed fire sequences, fencing options, and planting treatments and variation in the timing and degree of harvests (Brose et al. 2008, Loftis 1990, Steiner et al. 2008). In some circumstances, prescribed fire is recommended for both site preparation and release of existing oak seedlings from overtopping woody competition (Brose et al. 2008). The use of prescribed fire to release oaks from overtopping vegetation following the first removal cut of a shelterwood, referred to as the “shelterwood-burn technique” (Brose and Van Lear 1999), has been tested successfully in the Virginia Piedmont (Brose et al. 1999), but studies in the central Appalachians generally are lacking.

Our original objective was to design a study to test the shelterwood-burn technique in the mesic Allegheny Mountains of West Virginia. When this study was initiated in 2000, however, the

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understory included too few oak seedlings of competitive size relative to other woody species to conduct a shelterwood harvest. Therefore, we began by studying the effects of site preparation burning postulated to remove interfering competition and create conditions suitable for the establishment of new oak seedlings. Although these conditions have delayed the assessment of the original objective of this study (i.e., a test of the shelterwood-burn technique), it is a common situation on the landscape today, whereby small oak seedlings are present but overtopped by a dense layer of shade-tolerant woody vegetation (Nowacki and Abrams 2008).

Herein, we assess prefire and postfire conditions following two prescribed fires. In this paper, we focus on the effects on the seedling, sapling, and overstory strata. The study design included deer (*Odocoileus virginianus*)-exclosure fencing that allowed us to examine the effects of herbivory. After burning we also evaluated treatment effects on canopy characteristics to determine if levels of photosynthetic active radiation were altered relative to unburned control stands. We also include descriptive characteristics of the stand following the shelterwood harvest during the dormant season of 2009-10. Other information about this study is available pertaining to the effects of burning on acorn weevils (McCann at el. 2006), small mammals (Rowan et al. 2005), woodland salamanders (Ford et al. 2010), and the seed bank (Schuler et al. 2010).

METHODS

Site Description

Typical of the central Appalachians at low elevations to mid-elevations (< 3,000 feet), oaks dominate the overstory but are virtually absent from subcanopy strata. Moreover, dense understories of shade-tolerant species, such as striped maple (*Acer pensylvanicum*) and American beech (*Fagus grandifolia*), make it unlikely that new oak seedlings will develop into the larger individuals that will be competitive following a canopy disturbance. Furthermore, new acorns and oak seedlings are preyed upon by insects (Galford et al. 1991) and wildlife species currently abundant but formerly scarce during much of the 20th century (Horsley et al. 2003). As such, oak seedlings are ephemeral and do not persist for extended periods as in the past (Rentch et al. 2003).

Our study was conducted in the Canoe Run watershed of the Fernow Experimental Forest (39.03° N, 79.67° W) in West Virginia. The Fernow is in the Allegheny Mountains of the central Appalachian broadleaf forest (McNab and Avers 1994). The average growing season is 145 days (May to October) and the mean annual precipitation is about 56 inches, which is evenly distributed throughout the year (Pan et al. 1997). Growing season temperatures are typically moderate and growing season moisture deficits are uncommon (Leathers at al. 2000). Overstory species composition is complex and best described as mixed-mesophytic (Braun 1950) throughout much of the Fernow, but within the study area, northern red oak (*Quercus rubra*), chestnut oak (*Q. prinus*), and white oak (*Q. alba*) are the most common overstory species in descending order of importance as measured by basal area. Other common associates in the study area include red maple, sugar maple, black birch, and yellow-poplar (*Liriodendron tulipifera*).

Treatment areas for our study encompass approximately 77 acres in two separate locations approximately 0.15 miles apart. Site elevations range from about 2,000 to 2,500 feet above sea level. Site index is about 70 for northern red oak (Schnur 1937) throughout the study area. Sites with these

Table 1.—Weather and fire behavior characteristics for prescribed burns on the Fernow Experimental Forest, West Virginia

Date	Air[†] (°F)	RH[†] (%)	ROS[‡] (ft/min)	PT[‡] (°F)	WS[‡] (mi/h)	Days since rain
4/12/2002	73 - 72	38 - 39	30 (13)	576 (307)	3 (2)	3
4/4/2003	70 - 63	41 - 64	49 (49)	484 (190)	6 (1)	5
4/11/2005	70 - 72	13 - 12	144 (272)	621 (252)	5 (1)	3
4/15/2005	57 - 55	21 - 23	39 (30)	615 (151)	9 (1)	7

[†] Air temperature (Air) and relative humidity (RH) given for start and finish times of prescribed fires.

[‡] Rate of spread (ROS), maximum probe temperature (PT), and wind speed (WS) are means with standard deviations in parentheses.

values are considered good quality for timber production but are less productive than coves or side slopes with a more favorable aspect (Barrett 1995). The study area comprises a broad ridgetop and mostly west-facing side slopes. Soils are Calvin channery silt loam with a minor inclusion of a Gilpin channery silt loam. Calvin soils are well drained, moderately permeable, and strongly acid to very strongly acid. Natural fertility is moderate to moderately low. Gilpin soils are very strongly acid to extremely acid, are moderately permeable, and have moderately low fertility (Losche and Beverage 1967).

Experimental Design and Data Collection

Initial inventories revealed that a dense layer of shade-tolerant understory vegetation was present and would likely inhibit any positive response from the targeted oak seedlings following the first stage of shelterwood harvest. Therefore, we began our study by treating the majority of the study area with two prescribed fires just before the start of the growing seasons in 2002 and 2003, and 2005. The first prescribed fire in spring 2002 was interrupted due to unfavorable weather conditions, resulting in burning only a portion of the study area. The remainder of the study area not burned in 2002 was burned in 2003. In 2005, a second prescribed fire was conducted that resulted in more uniform effects throughout the study area. Fire behavior mostly was moderate to low intensity with flame lengths less than 3 feet resulting from the combustion of leaf litter and 1-hour surface fuels (Table 1). Strip head fires were used to manage fire intensity. Our objective was to minimize injuries to overstory trees and eliminate the shade-tolerant understory. More information on the fire and weather data can be found in Schuler et al. (2010).

We used a three-tier sampling scheme to measure the treatment response of seedling, sapling, and overstory strata through time. We monitored overstory response to treatments in twenty-four 0.5-acre growth plots. All but four of these plots were in the forest matrix treated with the two prescribed fires. We erected deer exclosure fencing in 2000 on half of the overstory growth plots in the forest matrix treated with prescribed fires. The unburned reference plots, primarily established for a concomitant herpetofauna (Ford et al. 2010) study allowed us to compare burned versus unburned portions of the stand. However, there were no fenced plots in the unburned portions of the study area, thereby preventing us from examining the interaction of no fire combined with deer exclosure fencing.

Within each overstory plot, we permanently tagged all stems 5.0 inches and larger in diameter at breast height (d.b.h.) following Lamson and Rosier (1984). All stems were identified by species, status (alive or dead), and d.b.h., and we noted stem characteristics such as fire damage. We defined the sapling size class as all woody stems 1.0 to <5.0 inches d.b.h.; all stems within this size range were permanently tagged and monitored by using the same measures as for overstory trees. We monitored saplings on ten 0.01-acre plots systematically distributed within each overstory plot for a total of 240 sapling-size plots throughout the study area.

We defined the seedling size-class as all woody stems less than 1.0 inch in d.b.h. and tallied seedlings by height class on twenty 0.001-acre plots systematically distributed within each overstory plot for a total of 480 plots. We defined height classes as all stems less than 6, 6 to <12, 12 to <36, 36 to <60, and ≥60 inches in total height but <1.0 inch in diameter. When we collected the data, we recorded seedlings and sprouts separately. However, the vast majority of all stems in this size category were true seedlings and we have combined both forms of regeneration for this analysis and refer to them as seedlings. In this paper, we conducted analyses based on all seedlings and those ≥12 inches in total height. For all three strata, we conducted pre-treatment inventories in 2000 and post-prescribed fire measurements in summer 2006 and 2009. Following the first removal cut of the shelterwood harvest during the dormant season of 2009-10, we collected overstory measurements again in 2010.

To assess the amount of solar radiation penetrating the canopy, we used a Nikon E8400 digital camera (Nikon Corp., Tokyo, Japan) coupled with a Nikon FC-E9 fisheye lens held within a self-leveling mount to take hemispherical canopy images at each plot. One image from the center of the plot at each time period was used for analysis. All images were oriented to magnetic north and taken at heights of about 4 feet, which was above the extant herbaceous layer. We took canopy imagery between August 15 and September 12 in 2007 and 2010. No images were taken before the prescribed burns; therefore, our analysis was limited to comparing twice-burned stands (n=20) to portions of the study area that have not been treated with prescribed fire (n=4).

We then conducted canopy analysis by using the WinsCANOPY system version 2006b (Regent Instruments Inc., Quebec, QC). Latitude and longitude were specified for each image and true north adjusted from magnetic north by using the local magnetic declination during analysis. Interactive masks were used to block any ground surface captured in the image due to slope characteristics. We defined the growing season for canopy analysis as May 1 to September 30. WinsCANOPY estimates numerous canopy parameters based on calculated solar tracks for specific locations and canopy characteristics. We report the under-canopy direct site factor (DSF), which is the ratio of the average daily direct radiation received under the canopy and the average daily direct radiation received over the canopy for the growing season expressed as a percentage. Because photosynthetic active radiation (PAR) is a constant percentage of total radiation, we used DSF as a surrogate for the amount of PAR penetrating the forest canopy to the height of the lens. We also report openness, which is the fraction of the total number of pixels classified as open sky, adjusted for the lens, in the canopy above the lens.

Data Analysis

We used repeated measures modeling with restricted maximum likelihood via SAS PROC MIXED (SAS Institute 2004) to evaluate treatment effects through time for seedling density by species (for all seedlings and seedlings >1.0 foot tall, hereafter referred to as larger seedlings), saplings, and overstory measures. We used a completely randomized design with year, fence, and plot as fixed effects. Both stem density (stems/acre) and basal area (feet^2/acre) were used as response factors for the sapling and overstory strata, whereas only stem density was evaluated for seedlings. The average characteristics for both seedlings and saplings served as the experimental unit for these strata in this paper. In other words, the average of 20 seedling plots and 10 sapling plots on one overstory plot at a point in time compose one experimental unit for each variable of interest.

During preliminary analyses, we included site (ridgetop versus sideslope) as an explanatory factor. Although some differences were found, meaningful ecological results related to the objectives of this study were not identified. Therefore, we present the results independent of any potential effects related to landscape position. We adjusted the denominator degrees of freedom by using the Kenward-Rogers method. In repeated measures analysis, the appropriate specification of the error covariance structure is an important part of the model-building process. After testing several covariance structures, we used the unstructured error covariance model because it generally produced the smallest Akaike information criterion values, resulted in significant p-values from the null model likelihood ratio test in all cases ($\alpha = 0.05$), and was appropriate for unequally spaced repeated measures.

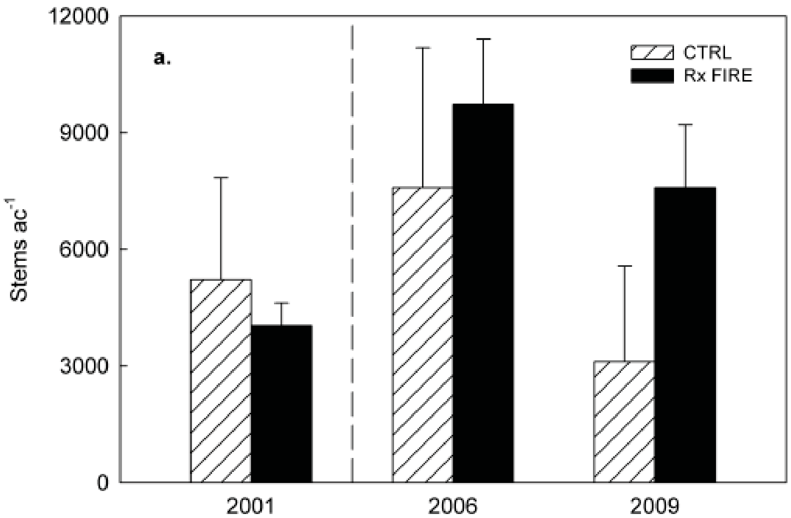
Significant values from the null model likelihood ratio test indicate the unstructured covariance matrix was a better fit than the ordinary least squares null model. Because we were specifically interested in fire effects through time, we excluded the unburned plots from our repeated measures analysis, which allowed us to examine year of observation as the explanatory variable for fire effects rather than evaluating more complex two-way and three-way interactions necessary if we included the control plots. Moreover, although we could not examine the interaction of no fires with fencing present, we include the control plots (i.e., no fire with no fencing) in the graphical presentation of our results for comparison purposes. We used the Tukey-Kramer mean separation test ($\alpha = 0.05$) to examine for individual differences in treatment levels and to interpret interactions between factors, when needed.

RESULTS

Seedlings

Repeated measures analysis indicated that year was a significant predictor of total oak seedling density ($p < 0.001$). Oak seedling density was greatest in 2006 after two prescribed fires as indicated by mean separation results, totaling almost 10,000 seedlings/acre (Fig. 1). Neither fencing ($p = 0.6794$) nor the year*fence interaction ($p = 0.9970$) was a significant predictor of oak seedlings. When we considered just oak seedlings >1.0 foot in total height, again year was the only significant factor in the repeated measures model ($p = 0.0045$). However, it was not until 2009 that the number of larger oak seedlings increased significantly as indicated by the Tukey-Kramer results. Before burning, there were only about 50 larger oak seedlings/acre and this level remained relatively unchanged in 2006 after burning, but by 2009 the density increased to more than 1,500 stems/acre. Northern red oak was the most abundant of the three oak species present. There were almost no larger oak seedlings in the unburned control plots at any time in the last decade (Fig. 1).

As expected, there was an abundance of maple seedlings throughout our sampling intervals, but prescribed fire did alter population levels ($p = 0.0031$). Maple seedling density was greatest before burning in 2001, decreased by about two-thirds in 2006 following the burn treatments,



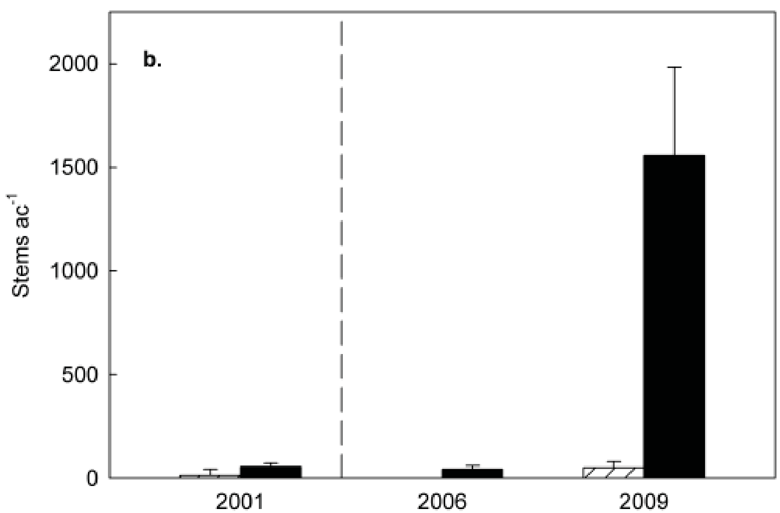


Figure 1.—Mean oak (includes northern red, chestnut, and white oak) seedling density (with standard error) through time for study areas on the Fernow Experimental Forest, West Virginia, subjected to two prescribed fires (n=20) and reference areas not treated with fire (n=4). a. Oak seedlings of all sizes; b. oak seedlings ≥12 inches tall. Dashed vertical line represents preconditions and post-conditions related to prescribed fires.

and recovered in 2009 (Fig. 2). The Tukey-Kramer results identified 2006 as unique, indicating the fire effects were short-lived. There was some evidence that the interaction of year and fencing ($p = 0.0502$) was contributing to the results as well. Most noteworthy observations occurred in 2009, when we found an average of 14,435 maple seedlings/acre in the unfenced plots and 6,990 seedlings/acre in the fenced plots. In 2001 and 2006 there were no meaningful deviations among fenced and unfenced results. There was no evidence that the interaction between year of observation and fencing carried over into larger maple seedlings ($p = 0.2488$), either. Larger maple seedling density differed only by year ($p = 0.0277$), with the preburn density significantly higher than the 2006 and 2009 observations (Fig. 2), suggesting the number of larger maple seedlings had yet to recover to preburn levels.

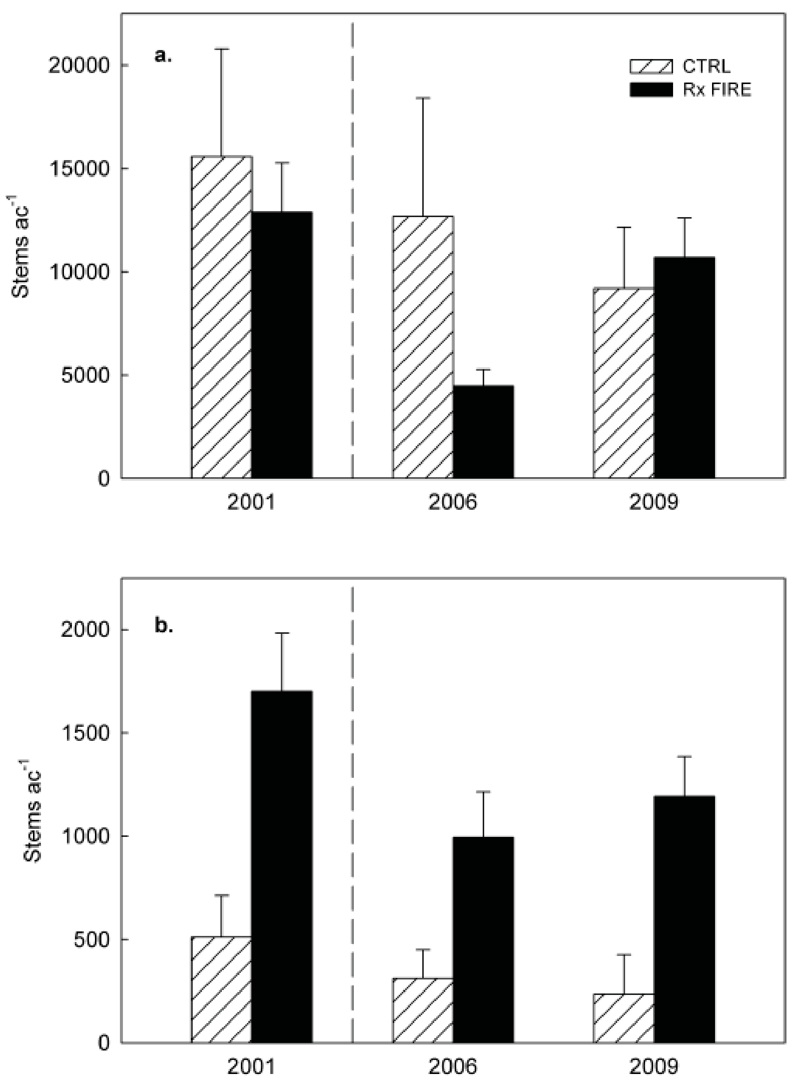


Figure 2.—Mean maple (includes striped, sugar, and red maple) seedling density (with standard error) through time for study areas on the Fernow Experimental Forest, West Virginia, subjected to two prescribed fires (n= 20) and reference areas not treated with fire (n=4). a. Maple seedlings of all sizes; b. maple seedlings ≥12 inches tall. Dashed vertical line represents preconditions and post-conditions related to prescribed fires.

The responses of black birch and yellow-poplar to prescribed fire were similar. Total birch (p = 0.0012) and yellow-poplar (p = 0.0010) seedlings varied by year in the repeated measures analysis and increased almost tenfold in 2006 after burning (Figs. 3 and 4). By 2009, total seedling densities for both species were beginning to decline, but densities of larger seedlings increased. It appears that many smaller birch and yellow-poplar seedlings were surviving and growing into larger seedlings in the understory environment. For larger seedlings alone, year of observation was the only significant model term for both birch (p = 0.0012) and yellow-poplar (p = 0.0101), but the increase was not significant until 2009 for either species according to the mean separation tests (Figs. 3 and 4).

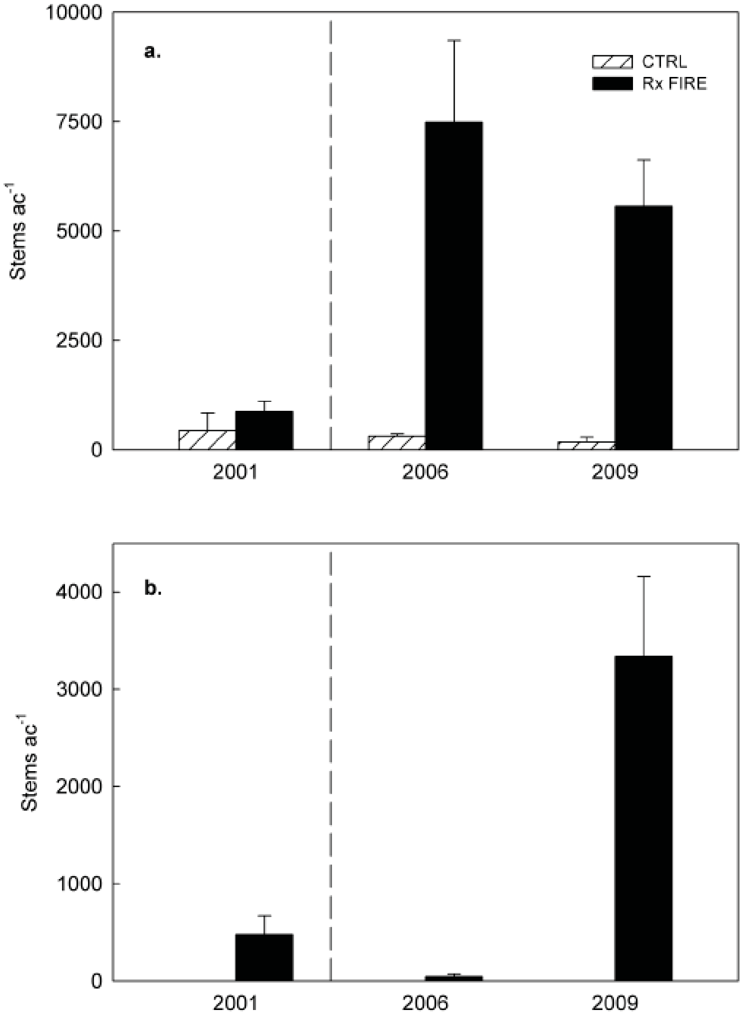


Figure 3.—Mean black birch seedling density (with standard error) through time for study areas on the Fernow Experimental Forest, West Virginia, subjected to two prescribed fires (n=20) and reference areas not treated with fire (n=4). a. Black birch seedlings of all sizes; b. black birch seedlings ≥12 inches tall. Dashed vertical line represents preconditions and post-conditions related to prescribed fires.

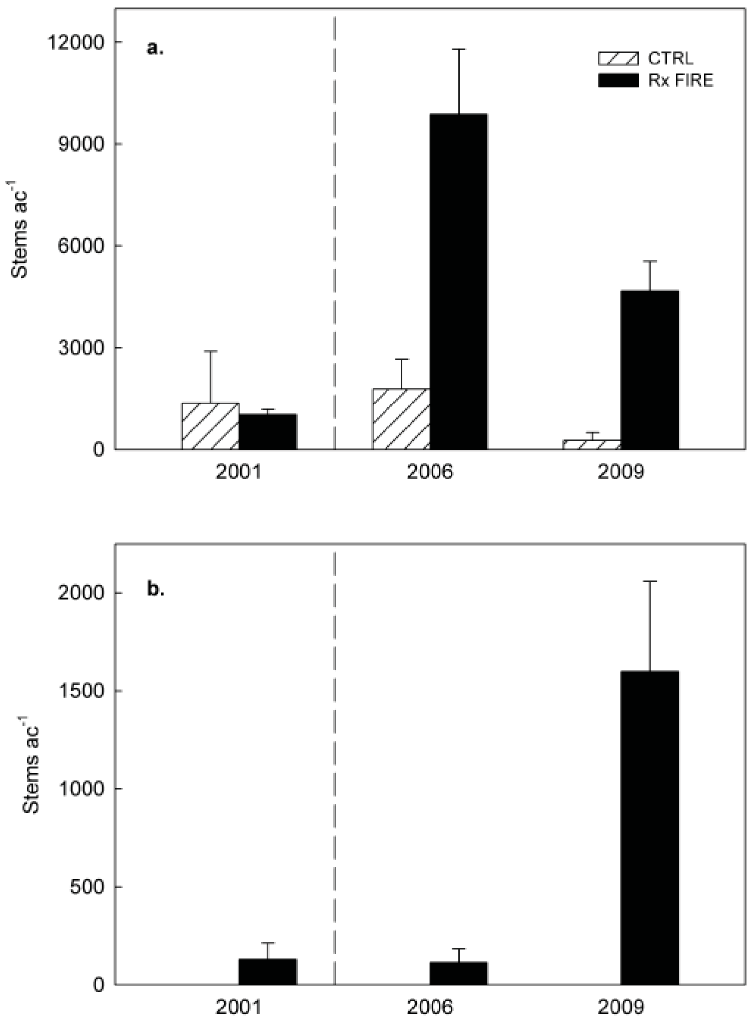


Figure 4.—Mean yellow-poplar seedling density (with standard error) through time for study areas on the Fernow Experimental Forest, West Virginia, subjected to two prescribed fires (n=20) and reference areas not treated with fire (n=4). a. Yellow-poplar seedlings of all sizes; b. yellow-poplar seedlings ≥12 inches tall. Dashed vertical line represents preconditions and post-conditions related to prescribed fires.

By 2009, areas treated with prescribed fire were supporting dense seedling populations totaling more than 7,500 seedlings/acre ≥1.0 foot in total height of oak, maple, birch, and yellow-poplar combined. Maple was the most abundant genera before burning, but after burning by 2009, maple (1,192/acre), oak (1,557/acre), and yellow-poplar (1,597/acre) seedlings ≥1.0 foot were approximately equally represented and birch was the most abundant species (3,337/acre). With respect to seedlings of this size (≥1.0 foot tall) and the burning treatments, oak, yellow-poplar, and birch all increased in density in response to prescribed fire treatments, whereas maple declined. Fencing had no meaningful effects on woody seedling population levels.

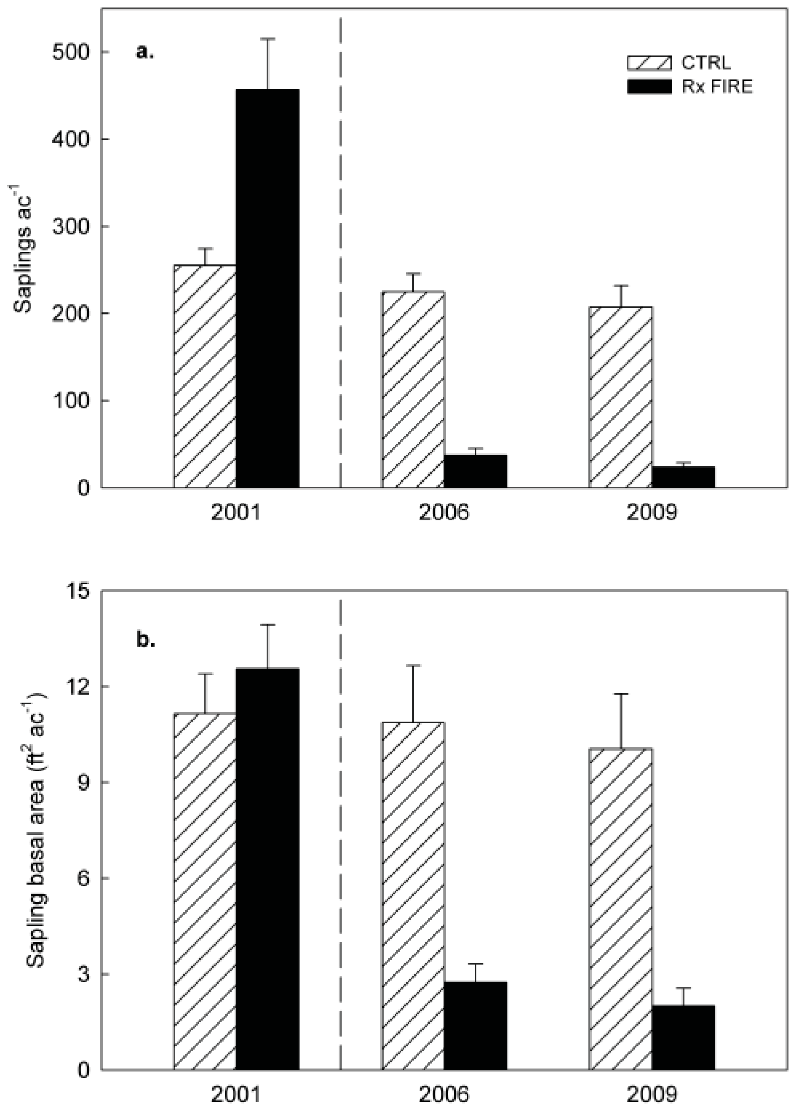


Figure 5.—Mean sapling-size tree abundance (with standard error) before (2000) and after (2006, 2009) two prescribed fires in terms of stem density (a) and basal area (b) on the Fernow Experimental Forest, West Virginia. Dashed vertical line represents preconditions and post-conditions related to prescribed fires.

Saplings

Before burning, the sapling layer was dominated by striped maple, American beech, and sugar and red maple in descending order of importance, and virtually no oaks were present. Following burning, species composition changes in the sapling layer were modest, but structural changes were well defined. Year of observation was a significant predictor of both sapling density ($p < 0.0001$) and basal area ($p < 0.0001$). After the prescribed fire treatments, sapling density was reduced by about 90 percent and basal area was reduced by almost 80 percent in 2006; both measures of sapling abundance continued to decline through 2009 (Fig. 5). Mean separation tests identified all three observation years as unique, suggesting the treatment effects from the prescribed burning were not fully realized in 2006. Sapling density and basal area in the control plots remained largely unchanged from 2000 to 2009 (Fig. 5).

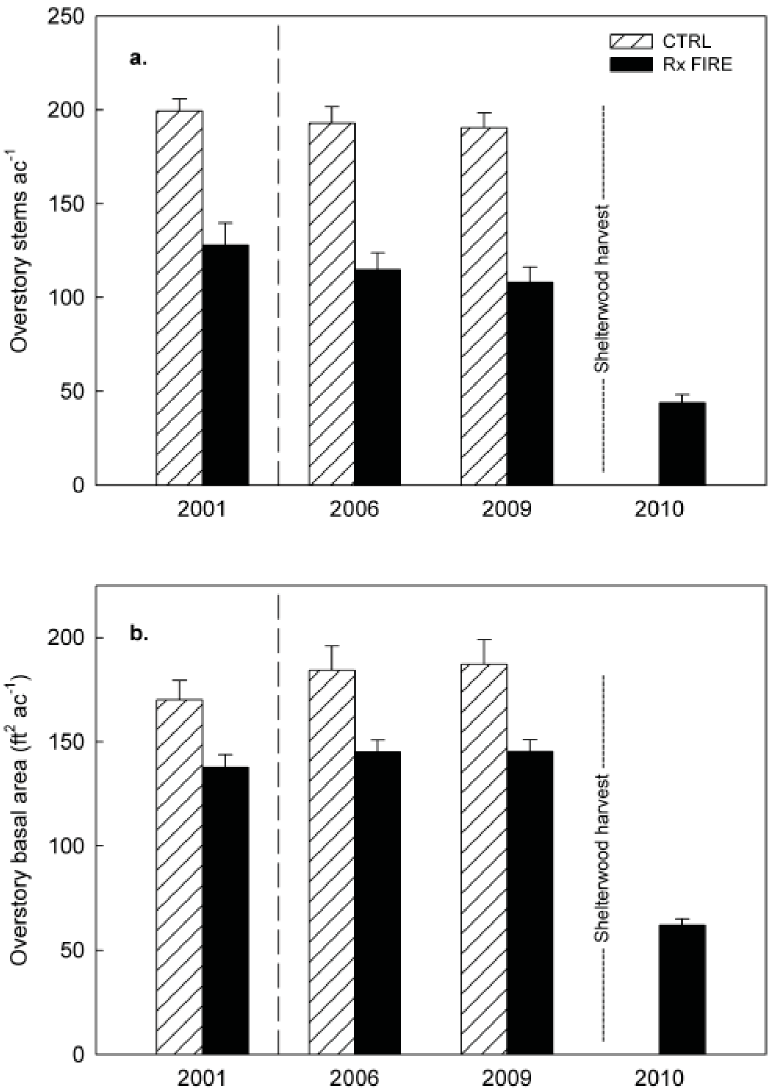


Figure 6.—Mean overstory tree abundance (with standard error) before (2000) and after (2006, 2009) two prescribed fires, and after the shelterwood harvest (2009-10) in terms of stem density (a) and basal area (b) on the Fernow Experimental Forest, West Virginia. Data for the unharvested reference areas not collected in 2010. Dashed vertical line represents preconditions and post-conditions related to prescribed fires.

Tracking individual stems allowed us to attribute the cause of stem death, which in the vast majority of the cases was fire effects, based on evidence of scorching and bark slough. Although not quantified, species composition of the seedling layer was not dominated by sprouts from dead sapling-size stems. Once again, fencing alone was not a significant predictor of either sapling density ($p = 0.9348$) or basal area ($p = 0.6318$), nor was the interaction between fencing and year of observation for either density ($p = 0.2383$) or basal area ($p = 0.7203$).

Overstory

Relative to burning, structural changes in the overstory were quite limited. Tree density declined through time ($p = 0.0034$) and each year was unique according to the mean separation tests, but without meaningful structural changes (Fig. 6). Year was also a significant explanatory factor of basal area ($p = 0.0009$), but unlike tree density, the level of basal area increased slightly from the preburn level in 2000 to the postburn measurements in 2006 and 2009. The percentage of overstory oak based on stem density increased slightly from 39.1 to 42.6 percent from 2000 to 2006. This increase occurred because the density of oaks remained constant whereas the absolute density of other species declined slightly. Fire-related mortality primarily affected the smaller subcanopy trees. American beech, sugar maple, and red maple were the species most commonly associated with fire-related mortality. In 2009 prior to the shelterwood harvest, overstory basal area averaged 145 feet^2/acre with 108 stems/acre (d.b.h. ≥5.0 inches); in 2010 after the first shelterwood harvest, overstory basal area averaged 62 feet^2/acre with about 44 stems/acre. Post-shelterwood residual stand basal area in 2010 varied from 56.1 to 68.1 feet^2/acre.

Canopy

Openness differed slightly between the burned and unburned portions of the study in 2007 during the first year of hemispherical canopy imagery ($p = 0.0261$). Mean openness was 8.9 and 7.2 percent for the burned and unburned portions of the study area, respectively. Maximum openness was 10.8 percent for the burned plots and 7.8 percent for the controls. Lacking a pretreatment canopy measurement, we cannot definitively attribute these differences to the prescribed fire treatments. Mean DSF, used as a surrogate for PAR, was 17.8 and 12.0 percent for burned and unburned plots, respectively in 2007, but there was little evidence to support real differences ($p = 0.1327$). Following the shelterwood harvest in 2010, mean DSF increased to 56.3 percent and openness increased to 36.7 percent, whereas these measures remained relatively constant in the untreated reference plots.

DISCUSSION

There were noteworthy vegetation dynamics in the study area related to prescribed burning and the shelterwood harvest. With the prescribed fire treatments, the silvicultural objective was to reduce interfering competition, primarily the shade-tolerant sapling layer, and this objective was largely successful. After two prescribed fires, sapling density was reduced by 90 percent in a forest where the understory stratum was a dominant feature. The postfire structural conditions were more open in appearance and atypical of mesic forest conditions found today in the central Appalachians (Fig. 7). Given the slow growth rate of understory maples and birches in fully stocked stands (Lorimer 1981) and the absence of any sapling recovery 4 years after the last prescribed fire in this study, we speculate that dense understories may not have had time to develop if pre-20th-century fire return intervals of about a decade characterized the disturbance regime as estimated in some locations of Kentucky, Ohio, Maryland, and West Virginia (McEwan et al. 2007, Schuler and McClain 2003, Shumway et al. 2001, Sutherland 1997).

Despite the encouraging understory structural changes brought about by prescribed burning, our results also illustrated that current seed bank characteristics may pose a major impediment to achieving oak regeneration or restoration goals. Seedling densities of birch and yellow-poplar increased dramatically after burning and earlier work has shown that these two species were the most abundant arboreal species stored in the seed bank before prescribed burning (Schuler et al. 2010). The results reported here suggest that the fires stimulated the germination of these species and many are now successfully developing in the understory. It is a primary objective of this study to understand if the postharvest prescribed fire yet to be implemented will be a sufficient deterrent of black birch and yellow-poplar dominance in the understory and favor oak as it did in the Virginia Piedmont (Brose and Van Lear 1998). We anticipate conducting the additional springtime prescribed

Figure 7.—Plot 4 in early spring 2002 before burning (A) and late summer 2006 after two prescribed fires in 2002 and 2005 (B) on the Fernow Experimental Forest, West Virginia. Note the absence of the dense sapling layer in 2006 and the high level of overstory stocking at both timess.

fire, most likely in April, in either 2013 or 2014, which is when we project the oak stems present in the study area will begin to be overtopped by faster-growing stems of other species.

As we look to the future for the full implementation of this study, we are encouraged by the greater abundance of oak seedlings in the areas treated with prescribed fire. Following the second prescribed fire, there was an unquantified but qualitatively abundant oak mast year in fall 2005. Oak seedlings consequently increased throughout the study area in 2006 and the persistence by 2009 was greater in the areas treated with fire. The dramatic increase in oak seedlings in 2006 coupled with the virtual elimination of the sapling layer met the conditions we stipulated to halt prescribed fire treatments, at least temporarily. As noted by Brose et al. (2008), the application of prescribed fire is recommended only during certain stages of stand development and use of prescribed fire in some situations may lead to lower oak survival (Alexander et al. 2008).

By 2009, the density of oak seedlings ≥1.0 foot in total height was about 30 times greater in the burned areas than in the unburned control plots or in the burn areas before the application of fire. This result suggests the conditions following two prescribed fires favored not only the persistence, but also the growth, of oak seedlings. Miller et al. (2004) demonstrated that removing the shade-tolerant understory in mesic mixed-oak forests will lead to improved root and shoot development in oak seedlings, as well as greater levels of survival. The prescribed fires also enhanced the competitive stature of oak in relation to maple. In 2001, maple seedlings (≥1.0 foot tall) outnumbered oak seedlings 30 to 1; by 2009 after two prescribed fires, the ratio was nearly equal but favored oak (Figs. 1 and 2).

Because oak and yellow-poplar were about equal in abundance in 2009 (for both small and larger seedlings), the competitive interaction in the coming years will hinge, in part, on the response of both species to the next prescribed fire as yellow-poplar seedlings are likely to outgrow all other species following a major canopy disturbance in the absence of fire (Brashers et al. 2004). Even though yellow-poplar is one of the fastest growing species, about 80 percent of the yellow-poplar seedlings were killed by a prescribed fire in Virginia (Brose and Van Lear 1998). Abundant black birch seedlings also pose a significant hurdle for oak regeneration in our study. Birch was the single most abundant arboreal species in the understory in 2009 and may exclude other species if left unchecked (Schuler and Miller 1995), but also may be vulnerable to mortality in the next prescribed fire. For example, in Connecticut, 76 percent of all regenerating birch stems were killed by a single prescribed fire following a clearcut harvest (Ward and Brose 2004).

In 2006, postfire stocking reductions in the sapling layer did not meaningfully alter the understory light environment. This finding supports other research that one or more prescribed fires did not increase the amount of irradiance reaching the understory (Alexander et al. 2008, Hutchinson et al. 2005). However, herbicide reductions of understory stems up to 7 inches in d.b.h did increase PAR from about 2 to 8 percent, which elicited a significant growth response in extant northern red oak seedlings (Miller et al. 2004). Northern red oak and yellow-poplar achieve maximum rates of photosynthesis at about 30 percent of PAR (Holmgren 2000, Phares 1971), well above light levels we estimated in the 2006 understory. However, after the first stage of the shelterwood harvest in 2009-10, light levels increased to more than 50 percent of DSF, a direct correlate of PAR. Therefore, neither species should be limited by irradiance levels, at least initially, in the coming years.

After more than a decade of work, including fence building and maintenance, two prescribed fires, annual data collection of some variables, and the first stage of the shelterwood harvest, we are on the verge of achieving the conditions we were striving for to test the shelterwood-burn technique for releasing established oak seedlings from faster-growing competitors. The post-shelterwood fire will complete the experimental treatments of this study. The response to that treatment will be evaluated over the following decade, illustrating that the oak regeneration process, as well as studies to understand it, require commitment and substantial time. Until then, the results reported here should be viewed as preliminary because the full experimental design of this study as conceived and planned has yet to be fully implemented. The reader is reminded year was a surrogate for fire in our model and we cannot be certain the effects we report as significant are due to fire alone, even though the unburned control plots exhibited little change through time. As we progress into the next stage of this research, the effects of fire, time, fencing, and landscape position will be fully evaluated. Until then, these preliminary results add to our understanding of oak ecology and 21st-century forest management.

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STUMP SPROUTING OF NORTHERN PIN OAK ON NUTRIENT-POOR SANDY SOILS IN CENTRAL WISCONSIN

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Abstract.—Coppice with two to three reserve trees per acre is the generally accepted practice (GAP) for rotating oak stands on nutrient-poor, sandy sites (colloquially called "scrub oak sites") in Wisconsin. The future stocking of the stand is therefore dependent predominantly on stump sprouts with varying levels of contribution from advance regeneration. Two groups of sites (four cut in 1998 and four cut in 2006) were measured to examine the success of the stump sprouts. On the sites harvested in 2006, more than 85 percent of stumps had sprouted during the first year after harvest (Mujuri and Demchik 2009). By 2010, 74 percent of those sprouts were at least 6 ft tall. On the sites harvested in 1998, 90 percent of regeneration plots sampled had at least one desirable timber species with 85 percent of the plots containing at least one viable oak seedling/sapling and 41 percent of these plots containing an oak at least 10 ft tall. The average sprout height measured across all sites was 24 ft. Although there was some variability between sites, the GAP of coppice with reserve trees does seem to be effective at regenerating scrub oak sites.

INTRODUCTION

In central Wisconsin, low quality oak stands, colloquially called "scrub oak," represent one of the largest cover types. This cover type is predominantly present on nutrient-poor sites consisting of sandy soils. The most common overstory species are northern pin oak (*Quercus ellipsoidalis*) and black oak (*Q. velutina*), although the more shade-intolerant quaking aspen (*Populus tremuloides*) and moderately tolerant red maple (*Acer rubrum*) are frequently found as well. Longer-lived species such as white pine (*Pinus strobus*), bur oak (*Q. macrocarpa*), and white oak (*Q. alba*) are also common associates. Scrub oak sites have lower productivity because the soils are nutrient poor and sandy. They may have site indices (base age of 50 years) as low as 35 to 50 ft. In comparison, a more mesic site might have a site index of greater than 60 ft.

Site managers can rely on the natural accumulation of advance regeneration as well as stump sprouts on scrub oak sites for regeneration after harvest. Stump sprouting can be a very dependable form of regeneration on drier sites, where it has a greater competitive advantage due to an extensive root system (Johnson et al. 2002). A larger root mass will also have a greater carbohydrate reserve (Johnson et al. 2002), which can directly influence stump sprouting ability and success (Tredici 2001). Many abiotic and biotic factors, such as moisture stress or defoliation by pests, can affect this carbohydrate reserve (Staley 1965, Thomas et al. 2002). Both of these studies concluded that a depletion of carbohydrate reserves was the primary cause for oak decline. Oak decline has shown to similarly reduce the overall sprouting rate of arboreal species (Tredici 2001).

The typical silvicultural generally accepted practice (GAP) for scrub oak sites is a coppice cut with 2 to 3 reserve trees per acre (Wisconsin Department of Natural Resources [DNR] 2006). A coppice cut

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is an overstory removal in which the primary form of regeneration and recruitment of trees into the overstory is asexual reproduction via stump or root sprouting with varying levels of contribution from advance regeneration. Oaks have a very high stump sprouting potential (Lynch and Bassett 1987, Mujuri and Demchik 2009, Weigel and Johnson 1998, Weigel and Peng 2002) and are very well suited for this type of harvest.

A wide variety of environmental factors affects oak regeneration although the two factors that seem to be the most limiting are water and light availability (Abrams 1988, Crow 1988, Johnson et al. 2002, Lorimer et al. 1994). Biological factors such as deer prevalence and competition from other species can also present a large hurdle to the predictable regeneration of an oak stand (Buckley et al. 1998, Chadwell and Buckley 2003, Crow 1988, Lorimer et al. 1994, Russell et al. 2001, Sander et al. 1984, Steiner et al. 2007).

Overall, regenerating oak on scrub oak sites seems to have a much higher degree of predictability. On these dry, nutrient-poor sites, oaks have a competitive advantage due to their moderate shade tolerance (Larsen and Johnson 1998) and good drought tolerance. Oaks can tolerate drought because of the large tap root that establishes early in the life of the seedling (Johnson et al. 2002). This tap root allows oaks to avoid the moisture stress experienced by other less adapted species (Chadwell and Buckley 2003). Another competitive advantage of this genus is that many species are vigorous stump-sprouters, even at maturity (Johnson et al. 2002).

Seed production and establishment is highly variable within oak and is subject to high levels of seed predation. For example, in a bumper crop year as much as 90 percent of the acorns may be rendered unviable by predation from mammals, insects, or other pests (Johnson et al. 2002). Stump sprouting allows for rapid growth with a high probability that the site will return to a largely oak-dominated overstory (Sander et al. 1984). Extensive studies have been conducted in Michigan (Lynch and Bassett 1987), Indiana (Weigel and Johnson 1998, Weigel and Peng 2002), and Wisconsin (Mujuri and Demchik 2009). These studies agree that even though sprouting decreases with age, coppicing dry sites is a viable regeneration method for the retention of oaks.

Mujuri and Demchik (2009) studied the stump sprouting success of northern pin oak in central Wisconsin on scrub oak sites. Initial data for our study were derived from their study. Mujuri and Demchik (2009) collected data in summer 2007 examining the percentage of stumps (in 1-inch diameter classes) that had sprouted the first season after harvest. Like Weigel and Johnson (1998) and Weigel and Peng (2002), they found a direct negative correlation between stump diameter and percentage of stumps sprouted. Mujuri and Demchik (2009) found that for stumps less than 4 inches in diameter the sprouting rate was almost 100 percent. The sprouting percentage decreased significantly as stump diameter increased, but for stumps greater than 18 inches in diameter the rate was still 71.4 percent.

For this study, data collection occurred during summer 2010, which provided a glimpse of stump sprout growth and success through time. For the purpose of this study, success was defined as having the dominant sprout reaching at least 6 ft tall, which was assumed to be beyond the height of heavy deer browsing of the terminal buds.

STUDY AREAS

Four sites previously studied for stump sprouting frequency of northern pin oak (Mujuri and Demchik 2009) were selected to provide the initial sprouting success data for this study. Two sites were in the Meadow Valley State Wildlife Area (average deer density of 27 deer per square mile the first 4 years after harvest) in Monroe County, and two sites were in the Sandhill State Wildlife Area (16 to 25 deer per square mile, 2007 to 2009). Both wildlife areas are managed by the Wisconsin DNR. These sites were harvested during winter 2006 to 2007 and were sampled in summer 2007 to assess the frequency of northern pin oak stump sprouting in relation to stump diameter and again in summer 2010 to assess the height growth of stump sprouts. Both sites are primarily northern pin, black, and white oak, with several scattered red (*Pinus resinosa*) and white pine per acre.

Both Meadow Valley and Sandhill State Wildlife Areas are characterized by dry, sandy soils formed on level sand plains. The dominant habitat types are *Pinus strobus/Euphorbia corollata* and *Pinus/Vaccinium-Gaultheria* (Kotar and Burger 1996). These two habitat types are very similar with the only difference being that the latter one often has a slightly higher water table and may be slightly less nutrient deficient.

Four additional sites, harvested in 1998, were selected in cooperation with the DNR (average deer density of 39 deer per square mile the first 5 years after harvest). These sites were not classified by habitat type but qualified as scrub oak sites on nutrient-poor, sandy soils. All four sites were located on privately owned land in Waushara County and ranged from 5 to 18 acres in size. Harvesting was done in winter according to standard Wisconsin DNR GAP for scrub oak, which is a coppice with two to three reserve trees per acre (Arend and Scholz 1969). These sites serve to add a temporal context to this study and examine the efficacy of regenerating oak using the harvesting system typical on scrub oak sites.

METHODS

Field Methods

Parallel transects were run across the longest axis of each site harvested in 2006. Any northern pin oak stump falling within 5 ft of the transect was measured for diameter, height of dominant sprout (measured in 1-ft height classes), and average percent browse of all sprouts by four levels (0-25% , 26-50%, 51-75%, and 76-100%). On each site 100 stumps were recorded along these transects. Height was measured using a graduated height pole constructed from polyvinyl chloride and marked in 1-ft increments.

More extensive sampling was conducted on the 12-year-old sites to assess regeneration from stump sprouts as well as advance regeneration. Preharvest data were provided by the DNR for seedling regeneration. In summer 2010 parallel transects were run across the longest axis of each site to measure 25 stumps, twenty 0.0014-acre regeneration plots (located every 66 ft along the transect), and all trees within 5 ft of the transect greater than 2 inches in diameter at breast height. These data were intended to be pilot data, but after preliminary data analysis the sites were determined to be relatively homogenous and variation was low enough that more sampling was not required.

Data Analysis

Descriptive statistics were conducted to determine the rate of success in reaching a height of at least 6 ft. These tests were performed in Microsoft Office Excel™ (Microsoft, Redmond, WA). Regression was also performed to determine if the height of the dominant sprout could be estimated using the outside bark diameter of the stump. The regression analysis was conducted using Minitab® 15.1.1 (Minitab, Inc., State College, PA) statistical software. Correlation between level of deer browsing and height of the dominant sprout was also analyzed.

The 12-year-old sites were analyzed to see if they meet the requirements for adequate stocking based on DNR standards (Wisconsin DNR 2006). According to these standards, at least 59 percent of the plots surveyed must be stocked with a viable seedling/sapling of a desired species. For the purposes of this study the following species were deemed desirable: any oak or maple, green (*Fraxinus pensylvanica*) or white ash (*F. americana*), and white or red pine. If this condition was not satisfied, the stump sprouts were then examined to determine if they would fill the gap that was left by inadequate advance regeneration from seed and seedling sprouts.

RESULTS

All sites were measured during summer 2010. On the sites harvested in 2006, 74.5 percent of the sprouts were at least 6 ft; the average height of the dominant sprout across all sites was 7.8 ft. The average stump diameter was 8.3 inches (Table 1). The percentage of stump sprouts in each browse category was highly variable within and across all sites (Table 2). With the alpha level set at 0.05, there was a significant correlation ($p > 0.001$) between stump diameter and height of the dominant sprout ($r = 0.299$). There was also a significant correlation ($p = 0.019$) between deer browsing and height of the dominant sprout.

On the sites harvested in 1998, 88.8 percent of plots were stocked with a desirable species; 85 percent of these plots were stocked with at least one viable oak seedling/sapling. Of those stocked with oak, 41 percent were stocked with an oak greater than 10 ft tall. The average height of stump sprouts measured was 24 ft (Table 3).

Stump Sprouting

Stump sprouts are a very effective tool for regenerating oak on nutrient-poor, sandy sites. They have the ability to quickly regenerate a site. In only four growing seasons roughly 75 percent of stump sprouts on these sites were able to achieve a height greater than the effective deer browse line. The data from the sites harvested in 1998 also demonstrate the rapid growth rates of these stump sprouts as they were able to achieve an average height of 24 ft in only 12 growing seasons. This height is beyond the predicted height based on site index curves assuming a base age of 50 and a site index between 40 and 50 ft, which is typical on these dry nutrient-poor sites (Carmean 1972).

A positive correlation was seen between the outside bark diameter of the stump and the height of the dominant sprout. The greater root mass of a larger stump would be able to gather more water and nutrients than a smaller stump and would also contain a greater store of carbohydrates. Although the r^2 was significant ($p > 0.001$), it was too low to allow for accurate prediction of sprout height from stump diameter. There are simply too many other variables that can affect height growth. If more

Table 1.—Average values of percentage of sprouts >6 inches, dominant sprout height, and stump outside bark diameter by site, Meadow Valley (MV) and Sandhill (SH) State Wildlife Areas

Site*	Sprouts >6 inches (%)	Avg. Sprout Ht. (ft)	Avg. Stump OB Diameter (in)
MV 826	80	9	9.8
MV 855	78	7	9.2
SH 105	66	8	5.9
SH 112	74	7	8.2
Average	75	8	8.3

*Site names used are Wisconsin DNR stand designations.

Table 2.—Stump sprouts (%) found in each browse category by individual site, Meadow Valley (MV) and Sandhill (SH) State Wildlife Areas

	Site			
Browse Category	MV826	MV855	SH105	SH112
0 - 25 %	23	72	12	74
25 - 50 %	49	22	37	23
50 - 75 %	18	5	38	3
75 - 100 %	10	1	13	0

*Site names used are Wisconsin DNR stand designations

Table 3. —Plots stocked with desirable species, plots stocked with oak, and plots with oak >10 ft (average percentages), and average stump sprout height, Waushara County sites

Site	Plots stocked with desirable species (%)	Plots stocked with oak (%)	Plots with oak >10 ft (%)	Average stump sprout height (ft)
1	95	90	75	25
2	90	95	50	20
3	70	55	10	26
4	100	100	30	24
Average	89	85	41	24

variables were to be entered into the equation, such as soils (moisture and texture), light availability, stresses, pests, or competing vegetation, an equation could possibly be developed to predict the growth of the dominant sprout more accurately.

Seedling Regeneration

Stump sprouts may provide for quick restocking of oak, but they are not the only contributor. Even on scrub oak sites, seedling regeneration can be a vital addition to the reliable stump sprout regeneration. On the sites harvested in 1998 extensive seed-origin regeneration was present. Black, northern pin, and white oak seedlings were prevalent across all sites. Whereas black and northern pin oaks tend to be relatively shorter-lived species, white oak can have a much longer life span. Much of the seed origin regeneration was white oak (present in 70 percent of plots), which gives further hope for the future of these stands.

Figure 1.—Six-year-old northern pin oak stump sprout in central Wisconsin.

Deer Browsing

One of the main concerns of many foresters for the future of oak is the effect that deer can have on regeneration.[2] A significant positive correlation ($r = 0.132$) between deer browsing and dominant sprout height was observed, implying one of two possibilities. Either deer will preferentially browse more successful sprout clusters as they are more nutrient rich, or the browsing that occurs reduces the competition, allowing the dominant sprout to be more successful. Although deer browsing may be a factor in the success of oak regeneration on scrub oak sites in general, for all of the sites used in this study it appears that sufficient oak stump sprouts (combined with other desirable components of regeneration) were produced to adequately regenerate the stands and the majority of stump sprouts were able to grow above the deer browse line.

The amount of browse observed was highly variable both across an individual site and between all four study sites as a whole. The form of a stump sprout may actually serve as a competitive advantage against deer browsing. The sheer volume of sprouts that typically occur (Fig. 1) would make it very difficult for a stump sprout to have all of its shoots browsed as some will naturally be protected by the surrounding shoots. Browsing was not examined for advance regeneration from seed, but as an average of 85 percent of plots were stocked with oak after 12 years it does not seem to be significantly detrimental, at least on scrub oak sites.

[2]Wisconsin Department of Natural Resources. 2006. Natural oak regeneration in Wisconsin survey. Unpublished survey.

Management Implications

In any management situation, sites should always be evaluated on an individual basis. If oak decline is present, different management actions may be required. A guide for managing oaks in Michigan recommended a sanitation harvest, salvage harvest, or letting the stand sit to allow a more natural progression, depending upon current conditions (Michigan DNR 2000). The main source of variation found in this study was site history. When the four sites harvested in 1998 were examined, one site appeared quite different from the others. Three of the sites had extensive seed-origin oak regeneration, whereas the seed-origin regeneration in the fourth was largely black cherry (*Prunus serotina* Ehrh.). This difference could be the result of previous agricultural use of the site. Despite this variation, even this site was successfully regenerated with economically desirable tree species based on the combination of oak stump sprouts and seedlings of a range of commercial species. The GAP called for on these nutrient-poor, sandy sites is an appropriate method for achieving full site regeneration.

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SILVICULTURAL OPTIONS FOR FORESTS THREATENED BY HEMLOCK WOOLLY ADELGID (*ADELGES TSUGAE*)

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Abstract.—Eastern hemlock (*Tsuga canadensis* [L.] Carr) is a common component of central hardwoods forests. Because hemlock tolerates low light, overstocked stands are common. The hemlock woolly adelgid (*Adelges tsugae*) (HWA), is a nonnative invasive insect that feeds on eastern hemlock. Currently, HWA is established in 17 states and is causing tree decline and wide-ranging mortality. Crown variables such as live crown ratio and crown density and transparency are accurate predictors of hemlock decline; more vigorous trees appear to be less vulnerable to HWA. We are experimentally applying silvicultural thinnings in stands prior to HWA invasion, as a means for improving crown vigor and increasing hemlock survival. Treated stands are located in the northern portion of eastern hemlock's range, where winter temperatures, combined with introduced biocontrols, may reduce the impacts of HWA. Current management guidelines recommend that thinning operations should remove at least 6 to 7 m^2/ha of basal area; however, if stands are overstocked, basal area removal should not exceed more than one-third of the total in any given operation. This presentation will report the changes in post-thinning stand structures resulting from modifications of current guidelines. Five-year growth response of hemlock crop trees will be reported for three Pennsylvania stands.

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DEVELOPMENT OF RED MAPLE REGENERATION 10 YEARS POST-HARVEST

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Abstract.—Red maple (*Acer rubrum* L.) is becoming increasingly dominant in forest stands throughout the eastern United States. To investigate the reasons for the increase, we examined the development of red maple and oak (*Quercus* spp.) seedlings and stump sprouts following the harvest of oak-dominated stands. We monitored 5,692 plots in 52 mixed-oak stands before harvest and 1 yr, 4 yr, 7 yr, and 10 yr after harvest across Pennsylvania. Through stump sprouts alone, red maple fully recaptured the amount of growing space it had previously occupied in the overstory 7 years after harvest. Red maple surpassed all oaks combined in rapid site capture through both seed-origin and sprout-origin regeneration. Red maple's superior ability to regenerate by sprouts is particularly favored by timber harvesting following a history of management and disturbance regimes that permit the accumulation of suppressed, small-diameter red maple stems. Among the events and processes that promote stand conversion, timber harvesting may be the major proximal cause of the widespread, increasing dominance of red maple.

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A GUIDE FOR MATCHING OAK SPECIES WITH SITES DURING BOTTOMLAND RESTORATION

David C. Mercker[1]

Abstract.—Over the past several decades, federal incentive programs have encouraged the restoration of bottomland forests throughout the West Gulf Coastal Plain and the Lower Mississippi Alluvial Valley. Programs such as the Conservation Reserve Program and the Wetlands Reserve Program have been marginally successful (Stanturf et al. 2001). Foresters and contractors often follow conventional tree planting procedures that are well established for upland sites, but prove problematic in bottomlands. High water tables, soil drainage and compaction, overland flooding, and diverse soil properties make species selection difficult. Slight changes in topography and soil structure often have a dramatic effect on survival and growth of planted oak seedlings (Hodges and Switzer 1979). This project documented the survival and growth of 6-year-old seedlings that were established in 2004 on a bottomland site at the West Tennessee Research and Education Center, Jackson, Tennessee. The purpose was to determine how soil drainage as indicated by mottling (specifically, the point of >50 percent gray color throughout the soil profile) affects the survival and growth of bottomland oak species. The findings suggest that practitioners plant Nuttall, pin, and overcup oaks in poorly drained soils. As the drainage improves, begin mixing in willow oak. In the best drained soils (if they exist), finish by including water, swamp chestnut, swamp white, Shumard, cherrybark, and bur oaks. Potential species diversity should expand as the soil drainage improves.

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WILDLIFE MANAGEMENT

NATURAL CAVITY CHARACTERISTICS AND CAVITY BIRD ABUNDANCE ON WEST VIRGINIA FORESTED ISLANDS OF THE OHIO RIVER

James T. Anderson and Karen A. Riesz[1]

Abstract.—Wildlife habitats connected with forested islands and their back channels (areas where commercial traffic is prohibited) on the Ohio River are valuable to diverse species. However, quantitative data on the importance of these areas to cavity-nesting birds are lacking. We compared cavity-nesting bird use and habitat between back and navigational channel sides of islands in 2000 and 2001. We observed 13 species of cavity-nesting birds. Total cavity-nesting bird abundance (number per 50-m-radius plot) was similar between the back and navigational channel sides, but abundance of downy woodpeckers (*Picoides pubescens* L.) was higher on the back than the navigational channel side. The back channel side contained more cavities in living and dead trees combined per plot than the navigational side. Most cavity characteristics (entrance height, width, inside height, and volume) were similar between navigational and back channel sites. Basal area was higher on the back channel than on the navigational channel side. The back channels can support more cavity-nesting birds than the navigational channel side and this study adds to the growing literature base indicating that the more forested and isolated back channel areas are important to a variety of wildlife species.

INTRODUCTION

Bottomland hardwood forests play an important role in riverine systems. The movement of nutrients through a riparian ecosystem can alter the water quality of rivers and streams (Brinson et al. 1981). Bottomland hardwood wetlands are known for high wildlife species richness, in part because forested wetlands serve as transitional areas between uplands and bodies of water for a variety of wildlife (Wigley and Lancia 1998). The moist soil on bottomland sites increases understory vegetation, which can increase bird abundance (Dickson 1978). Dead woody vegetation serves as sites for cover, food, and breeding; and tree roots provide cover for aquatic invertebrate and fish communities (Brinson et al. 1981, Wigley and Lancia 1998).

Only 1.5 percent of the United States is composed of riparian ecosystems (Brinson et al. 1981). In 1937, bottomland hardwoods covered 4.8 million ha but decreased to 2.1 million ha by 1977 (Brinson et al. 1981). Bottomland hardwood forests were originally cleared for agriculture because of the high soil fertility (Kellison et al. 1998). The removal rate of the forests was particularly high during the 1960s and 1970s, when the price received for farm crops, particularly soybeans, increased substantially (Kellison et al. 1998). Conversion of forests to agricultural land and reservoirs causes the greatest threat to birds within bottomland hardwoods (Chapman and Chapman 1999, Dickson 1978).

Destruction and conversion of bottomland hardwoods to agriculture and development alters plant and animal communities. Removal of bottomland hardwoods may make the area susceptible to exotic

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species, parasites, predators, and diseases that affect native wildlife species (Harris and Gosselink 1990, Hoover 2005). Converting land from natural forests to tree plantations often results in lower bird species abundance and diversity (Dickson 1978). Kilgo et al. (1998) found that the narrow stands of bottomland hardwoods remaining from previous land management practices might not provide suitable habitat for forest birds that require interior habitat.

The Ohio River, flowing from Pennsylvania to Illinois, provides valuable habitats for a variety of species (Tolin and Schettig 1983). Aquatic habitats connected with the Ohio River islands and their back channels (i.e., areas behind islands without commercial boat traffic) provide some of the area's highest quality bottomland hardwood, riverine, and wetland habitats, and are used by a variety of birds, fishes, and mussels (Tolin and Schettig 1983, Zadnik et al. 2009). Specifically, the back channels are thought to be important to wildlife because they provide protection from disturbances such as wind and commercial navigation (Zadnik et al. 2009). However, quantitative data on bird populations and habitat on the islands and back channels are lacking. Resource management agencies need quantitative data on the islands and particularly the back channel areas, which are under increasing pressure for development. Our objectives were to compare breeding bird abundance and habitat characteristics for cavity-nesting birds between back channel and navigational channel sides of islands on the Ohio River to determine if the back channel areas deserved additional protection from development.

STUDY AREA

We conducted the study on 10 islands of the Ohio River Islands National Wildlife Refuge from Paden City to Vienna, West Virginia, within Wetzel, Tyler, Pleasants, and Wood Counties (Zadnik et al. 2009). The average size of the islands was 42.7 ha (SE = 9.2), and the back channels ($\bar{x}$ = 153.9 m, SE = 22.6) were generally half the size of the navigational channels ($\bar{x}$ = 341.1 m, SE = 18.5). Vegetation communities included mature and immature bottomlands, early and late old fields, and agricultural fields. Islands were located in the Western Hills avifauna region (Buckelew and Hall 1994). Long-term precipitation averages 111.8 cm (range = 65.4 - 153.2 cm) (National Climatic Data Center 2003).

METHODS

We conducted this study in spring and summer 2000 and 2001. In 2000, we established two 50-m-radius plots on each of 10 islands, with one plot on the back channel side and one plot on the navigational side. In 2001, we established two additional plots on each island, to make a total of two plots on the back channel side and two plots on the navigational side.

We established the plots in the oldest available stands, with trees >50 years old in most cases. We delineated the stands based on cover type maps from September 1993 imagery. We located the center points of the plots near the shoreline so that half of the plots covered the island and half covered the water. By using this approach, we eliminated the risk of plots touching shores on both sides of the islands, and maximized the amount of shoreline edge that could be surveyed, because this area was the focus of the study. Plots on all islands, except for two, were at least 250 m apart ($\bar{x}$ = 727.8 m; SE = 76.4; range = 129.4 - 2,470.3 m) for independent wildlife sampling (Ralph et al. 1995), unless the size of the island or availability of bottomland hardwood stands prevented this distance. Study plots, but not islands, were devoid of artificial nest boxes.

We used single observer fixed-radius point counts (Ralph et al. 1995) to quantify overall breeding bird abundance twice between May 24 and July 7 in 2000 and 2001 (Dettmers et al. 1999). This time period provided information for the breeding season of most birds. We surveyed each plot for 10 minutes between 0600 and 1030 (Rodewald and Smith 1998).

We initially conducted a prism count of trees within each plot with a 10 basal area factor prism. For trees tallied with the prism we recorded tree species, diameter at breast height (d.b.h.) (cm), presence or absence of cavities (Cline et al. 1980, Mannan et al. 1980), and tree height (m) (Raphael and White 1984, Runde and Capen 1987, Sedgwick and Knopf 1990, Swallow et al. 1986). We recorded canopy cover for the shoreline centers of each plot in 2001.

Once the prism count was completed, we searched all living and dead trees within the plot for cavities following Kahler and Anderson (2006). We surveyed trees if ≥50 percent of the trunks fell within the 50-m-radius plot boundary. For all standing trees within the plot that contained cavities, we recorded tree species, d.b.h., tree height, number of shelf fungi or conks (Dobkin et al. 1995, Raphael and White 1984, Runde and Capen 1987), decay class (Maser et al. 1979), and distance to the Ohio River. We then collected data for the number of cavities per tree, height of each cavity above ground, entrance hole width, entrance hole height, cavity volume, compass direction of cavities, and cavity origin (Oli et al. 1997, Soulliere 1988, Swallow et al. 1986). We assessed the origin of a cavity by using five categories: woodpecker-excavated holes, limb holes (due to the loss of a fallen branch), chimneys (stumps with a cavity at the top), all other cavities that do not fit the above descriptions (Carlson et al. 1998), and limb hole enlarged by woodpeckers.

We also collected data for cavity breadth and height inside the cavity. We termed the measurement from the front of the cavity to the back "cavity breadth." For cavities that could not be measured directly (i.e., trees were too unstable to climb or cavities were too high) we made estimates by using the minimum values observed for similar tree sizes. We did not measure or count cavities that were <2 cm in height and width. We also did not consider cavities suitable if they contained water or excessive debris, or if they were constructed so that a nest would not be well hidden or protected by weather (Robb 1986).

We used a randomized block analysis of variance (ANOVA) to compare basal area per plot (m^2/ha), prism tree d.b.h. (cm/plot), mean number of cavities per tree per plot, mean cavity trees per plot, and percentage canopy cover (dependent variables) between treatments (back channel side and navigational side, and years [independent variables]) in which the effects of the islands were blocked. We found particular cavity characteristics per tree (entrance height, width, inside height, and volume [dependent variables]) to be correlated (r^2 range = 0.171 - 0.805, $P < 0.05$), so we compared them between treatments (back channel side and navigational side, and years [independent variables]) with a multivariate analysis of variance.

We compared canopy cover, cavity breadth, height from ground, number of fungal conks, tree height, cavity tree d.b.h., and distance to water (dependent variables) between treatments and years (independent variables) with randomized block ANOVAs. We analyzed all variables across both living and dead trees to maintain adequate sample sizes and to include all current resources for cavity-nesting birds. We analyzed cavity origin and cavity tree decay class (dependent variables) between treatments and years (independent variables) with a *G*-test (Sokal and Rohlf 1995, Zar 1999). Cavity orientation for woodpecker-created holes was analyzed for circular uniformity by using Rayleigh's *z*-test (Zar 1999, Zwartjes and Nordell 1998). We compared differences in orientation (dependent variables) between channel sides (independent variables) for 2000 and 2001 with Watson's test (Rendell and Robertson 1994, Zar 1999). We compared tree species (dependent variables) of cavity trees between treatments and years (independent variables) with a *G*-test (Sokal and Rohlf 1995, Zar 1999). We used Friedman's nonparametric block test to compare native cavity bird abundance, total cavity bird abundance (includes European Starlings [*Sturnus vulgaris* L.]), and cavity bird species (dependent variables) between island sides, years, and the island-side interaction term (independent variables).

We considered all tests significant at $P < 0.05$. We transformed density data with square root transformation to meet normality and homogenous variance assumptions (Sedgwick and Knopf 1990, Sokal and Rohlf 1995). We log transformed cavity characteristics and tree height from ground, d.b.h., number of fungal conks, and distance to water; rank-transformed tree height and Maser decay class (Conover and Iman 1981); and arcsine transformed canopy cover (Zar 1999).

We analyzed relations between cavity and cavity tree characteristics (cavity volume, cavity breadth, height from ground to cavity, cavity tree height, cavity tree d.b.h., number of conks, and cavity tree distance to water) and cavity birds (abundance, richness, and diversity) with stepwise multiple regression ($P < 0.05$). Cavity volume was chosen to represent entrance height, width, and inside height because the variables were highly correlated (Sacilotto 2002).

RESULTS

Habitat Characteristics

The tree species that had the most importance (Spurr and Barnes 1980), or influence, on the composition of the plots were silver maple (*Acer saccharinum* L.), box elder (*Acer negundo* L.), pawpaw (*Asimina triloba* L.), black walnut (*Juglans nigra* L.), black locust (*Robinia pseudoacacia* L.), sycamore (*Platanus occidentalis* L.), and Eastern cottonwood (*Populus deltoids* Bartr.). Basal area was higher on the back channel ($\bar{x}$ = 42.03 m^2/ha, SE = 3.11) than on the navigational channel ($\bar{x}$ = 27.24 m^2/ha, SE = 1.99) side ($F_{1,9}$ = 43.51, $P < 0.001$). There was no interaction between side and year ($F_{1,9}$ = 0.195, P = 0.197) for basal area. There was an interaction between side and year ($F_{1,9}$ = 6.07, P = 0.029) for d.b.h. of the trees located in the prism count, but treatment effects by year showed no differences in 2000 (back channel: $\bar{x}$ = 57.27, SE = 5.76; main channel: $\bar{x}$ = 53.78, SE = 3.89; $F_{1.9}$ = 0.001, P = 0.974) or 2001 (back channel: $\bar{x}$ = 55.13, SE = 3.96; main channel: $\bar{x}$ = 44.71, SE = 3.58; $F_{1.9}$ = 1.84, P = 0.208).

Cavity abundance (cavities/plot) was higher on the back channel ($\bar{x}$ = 19.93, SE = 2.48) than on the navigational channel ($\bar{x}$ = 11.58, SE = 1.73) side ($F_{1,9}$ = 35.39, $P < 0.001$). Cavity tree abundance (trees/plot) also was higher on the back channel ($\bar{x}$ = 10.15, SE = 1.28) than on the navigational ($\bar{x}$ = 6.45, SE = 0.85) side ($F_{1,9}$ = 21.34, P = 0.001). There was no interaction between side and year for cavity abundance ($F_{1,9}$ = 0.57, P = 0.469) or number of cavity trees ($F_{1,9}$ = 0.62, P = 0.450).

Table 1.—Characteristics of cavities, cavity trees, and 50-m-radius plots between back channel and navigational channel sides of islands (n=10) on the Ohio River Islands National Wildlife Refuge, West Virginia, 2000-2001

	Back channel side		Navigational side	
Variable	$\bar{x}$ †	SE	$\bar{x}$ †	SE
Cavity characteristics				
Height of entrance (cm)	10.49 a	0.62	10.16 a	0.62
Width of entrance (cm)	6.77 a	0.20	6.95 a	0.29
Height inside cavity (cm)	11.98 a	0.99	11.57 a	1.14
Volume (cm^3)	2,623.04 a	719.41	2,860.36 a	902.89
Breadth (cm)	8.16 a	0.37	8.47 b	0.51
Height from ground to cavity (m)	7.30 a	0.25	6.60 b	0.27
Cavity tree characteristics				
Cavity tree height (m)	15.97 a	0.38	14.52 a	0.44
Cavity tree d.b.h. (cm)	55.7 a	1.84	47.72 b	1.84
Conks (no.)	1.19 a	0.32	0.64 a	0.25
Cavity tree distance to water (m)	14.00 a	0.61	17.42 b	1.00
Plot characteristics				
Canopy cover (%)	95.43 a	3.42	86.60 b	4.57

† Means in a row followed by the same letter are not different (P > 0.05) between the back channel and navigational channel sides.

Table 2.—Cavity origin per 50-m-radius plot between the back channel and navigational channel sides of islands (n=10) on the Ohio River Islands National Wildlife Refuge, West Virginia, 2000-2001

		Number of Cavities					
Year	Origin†	Back channel	Navigational channel	Total	Cavities (%) ‡	G-test	P-value
2000	1	75	47	122	37.3 a	1.84	0.605
	0.5	6	4	10	3.1 a		
	2	121	55	176	53.8 a		
	3, 4	12	7	19	5.8 a		
2001	1	129	114	243	40.1 a	10.49	0.015
	0.5	25	12	37	6.1 ab		
	2	204	104	308	50.8 b		
	3, 4	11	7	18	3.0 ab		

†Index of origin: 1 = woodpecker-excavated holes, 2 = limb holes, 3 = chimneys, 4 = all other cavities not described above (Carlson et al. 1998), 0.5 = limb holes enlarged by woodpeckers.

‡The same letter following values in this column indicates no difference ($P > 0.05$) in proportion of cavities of particular origin.

Cavity characteristics (entrance height, width, inside height, and volume) were similar between back and navigational channel sides (Wilks' $\lambda = 0.485$, $P = 0.291$) and there were no interactions between side and year for any cavity or cavity tree characteristic ($P \geq 0.320$). Cavity breadth was lower on the back than the navigational channel side ($F_{1,9} = 5.55$, $P = 0.043$; Table 1). Cavity height from ground was higher on the back channel than the navigational side ($F_{1,9} = 6.32$, $P = 0.033$). Generally, the origins of most cavities were limb holes (Table 2). In 2000, types of cavities were similar between the channel sides ($G_{1,3} = 1.84$, $P = 0.605$). In 2001, there was a significant difference between the types of cavities and channel side, with a higher proportion of limb holes on the back channel side ($G_{1,3} = 10.50$, $P = 0.015$).

Table 3.—Cavity tree decay class per 50-m-radius plot between the back channel and navigational channel sides of islands (n=10) on the Ohio River Islands National Wildlife Refuge, West Virginia, 2000-2001

Year	Decay class[†]	Number of trees: Back channel	Number of trees: Navigational channel	Total	Percentage of trees[‡]	G-test	P-value
2000	1	67	28	95	55.6 a	6.75	0.080
	2, 3	36	22	58	33.9 a		
	4	2	6	8	4.7 a		
	5, 6, 7	8	2	10	5.8 a		
2001	1	139	71	210	65.4 a	23.76	< 0.001
	2	41	41	82	25.5 b		
	3	1	5	6	1.9 bc		
	4	3	14	17	5.3 cd		
	5, 6	4	2	6	1.9 bd		

[†]Maser decay classification: 1 = live, 2 = declining, 3 = dead, 4 = loose bark, 5 = clean, 6 = broken, 7 = decomposed, 8 = down material, 9 = stump (Maser et al. 1979).

[‡]The same letter following values in this column indicates no difference (P > 0.05) in proportion of trees of particular decay class.

Cavity tree height ($F_{1,9}$ = 3.10, P = 0.112), and number of fungal conks ($F_{1,9}$ = 0.73, P = 0.415) were similar between channel sides (Table 1). Cavity tree d.b.h. was higher on the back channel than the navigational side ($F_{1,9}$ = 6.68, P = 0.030), but cavity tree distance to water was shorter on the back channel than the navigational side ($F_{1,9}$ = 13.63, P = 0.005). Plot canopy cover (percent) was higher on the back channel than the navigational side ($F_{1,9}$ = 10.38, P = 0.011). Maser decay class of the cavity trees was similar between channel sides in 2000 ($G_{1,3}$ = 6.75, P = 0.080) (Table 3), but in 2001, there was a difference between the decay class and channel side, with more live healthy trees than trees showing signs of senescence ($G_{1,4}$ = 23.76, P < 0.001).

The entrances of woodpecker-created cavities were randomly distributed with respect to compass direction for both sides and years combined (z = 0.0204, n=364, P > 0.05). Orientation was similar between the back channel side (BC) and navigational side (NC) for 2000 (Watson's U^2 = 0.1779, n_{BC}=75, n_{NC}=47, P > 0.05) and 2001 (Watson's U^2 = -0.0009, n_{BC}=128, n_{NC}=114, P > 0.50).

In both years, most trees containing cavities were silver maple, box elder, and black locust (Table 4). Differences were found between tree species containing cavities in 2000 (G_{10} = 64.68, P < 0.001) and 2001 (G_{12} = 520.48, P < 0.001). In 2000, box elder, hackberry (*Celtis occidentalis* L.), sycamore, silver maple, sweet buckeye (*Aesculus octandra* Marsh.), and black cherry (*Prunus serotina* Ehrh.) contained the highest proportion of cavity trees. Black locust, black willow (*Salix nigra* Marsh.), slippery elm (*Ulmus rubra* Muhl.), and black walnut contained the lowest proportion of cavity trees. In 2001, Eastern cottonwood, sycamore, box elder, silver maple, hackberry, black locust, and black cherry contained the highest proportion of cavity trees. Tree-of-heaven (*Ailanthus altissima* P. Mill. Swingle), slippery elm, black willow, black walnut, and pawpaw contained the lowest proportion of cavities.

Table 4.—Proportion of trees containing cavities for 2000 and 2001 on islands (n=10) on the Ohio River Islands National Wildlife Refuge, West Virginia, 2000-2001

Year†	Species	Scientific name	Cavity trees	Total trees	Cavity trees (%)‡
2000	Box elder	*Acer negundo*	39	162	24.1 a
	Hackberry	*Celtis occidentalis*	6	31	19.3 a
	Sycamore	*Populus occidentalis*	7	37	18.9 ab
	Silver maple	*Acer saccharinum*	95	531	17.9 ab
	Sweet buckeye	*Aesculus octandra*	1	3	33.3 abc
	Black cherry	*Prunus serotina*	2	12	16.7 abc
	Black locust	*Robinia pseudoacacia*	11	134	8.2 bc
	Black willow	*Salix nigra*	4	67	6.0 bc
	Slippery elm	*Ulmus rubra*	1	25	4.0 bc
	Black walnut	*Juglans nigra*	5	206	2.4 cd
2001	Others§		8	9	88.9 a
	Eastern cottonwood	*Populus deltoides*	6	13	46.2 ab
	Sycamore	*Populus occidentalis*	15	37	40.5 b
	Box elder	*Acer negundo*	60	162	37.0 b
	Silver maple	*Acer saccharinum*	171	531	32.2 b
	Hackberry	*Celtis occidentalis*	7	31	22.6 bc
	Black locust	*Robinia pseudoacacia*	29	134	21.6 c
	Black cherry	*Prunus serotina*	2	12	16.7 cd
	Tree -of-heaven	*Ailanthus altissima*	6	47	12.8 c
	Slippery elm	*Ulmus rubra*	3	25	12.0 cde
	Black willow	*Salix nigra*	7	67	10.4 cde
	Black walnut	*Juglans nigra*	7	206	3.4 d
	Pawpaw	*Asimina triloba*	1	937	0.1 f

†Differences were found between tree species containing cavities in 2000 (G_{10} = 64.68, P < 0.001) and 2001 (G_{12} = 520.48, P < 0.001).

‡ The same letter following values in this column indicates no difference (P > 0.05) in proportion of trees containing cavities between species.

§Includes catalpa (*Catalpa* spp.), sassafras (*Sassafras albidum* [Nutt.] Nees), sweet buckeye, and sweet cherry (*Prunus avium* L.).

Cavity Birds

We observed 13 species of cavity-nesting birds during point counts (Table 5). A total of 111 native cavity-nesting birds were recorded, 63 on the back channel side and 48 on the navigational side. Total native cavity-nesting bird abundance was similar between the back channel and navigational channel sides ($\chi^2_{1,9}$ = 1.80, P = 0.180) (Table 5). When European starlings were added to the cavity-nesting bird group, differences remained similar between sides ($\chi^2_{1,9}$ = 0.05, P = 0.823) (Table 5).

Abundance of downy woodpeckers (*Picoides pubescens* L.) was higher on the back channel than the navigational channel side ($\chi^2_{1,9}$ = 7.20, P = 0.007), but abundance of Carolina chickadees (*Poecile carolinensis* Audubon) ($\chi^2_{1,9}$ = 1.80, P = 0.180), Carolina wrens (*Thryothorus ludovicianus* Latham) ($\chi^2_{1,9}$ = 3.20, P = 0.074), European starlings ($\chi^2_{1,9}$ = 0.80, P = 0.371), great crested flycatchers (*Myiarchus crinitus* L.) ($\chi^2_{1,9}$ = 0.20, P = 0.655), hairy woodpeckers (*Picoides villosus* L.) ($\chi^2_{1,9}$ =

Table 5.—Cavity-nesting bird abundance (number of birds/plot) between the back channel and navigational channel sides of islands (n=10) on the Ohio River Islands National Wildlife Refuge, West Virginia, 2000-2001

	Back channel		Navigational channel	
Variable	$\bar{x}$ †	SE	$\bar{x}$ †	SE
Native cavity bird abundance ‡	0.91 a	0.14	0.73 a	0.15
Total cavity bird abundance §	1.10 a	0.19	1.19 a	0.21
Carolina chickadee	0.14 a	0.05	0.05 a	0.02
Carolina wren	0.13 a	0.05	0.04 a	0.02
Downy woodpecker	0.23 a	0.05	0.11 b	0.04
European starling	0.19 a	0.07	0.46 a	0.18
Great crested flycatcher	0.00 a	0.00	0.03 a	0.03
Hairy woodpecker	0.06 a	0.03	0.03 a	0.02
House wren	0.05 a	0.03	0.08 a	0.05
Northern flicker	0.11 a	0.04	0.06 a	0.04
Pileated woodpecker	0.05 a	0.03	0.01 a	0.01
Red-bellied woodpecker	0.05 a	0.03	0.01 a	0.01
Tree swallow	0.01 a	0.01	0.14 a	0.09
Tufted titmouse	0.06 a	0.03	0.11 a	0.06
White-breasted nuthatch	0.01 a	0.01	0.06 a	0.04

†Means pairs followed by the same letter are not different (P > 0.05) between the back channel and navigational channel sides.

‡ Cavity bird abundance without European starlings.

§ Cavity bird abundance with European starlings.

1.25, $P = 0.264$), house wrens (*Troglodytes aedon* Vieillot) ($\chi^2_{1,9} = 0.20$, $P = 0.655$), northern flickers (*Colaptes auratus* L.) ($\chi^2_{1,9} = 3.20$, $P = 0.074$), pileated woodpeckers (*Drycopus pileatus* L.) ($\chi^2_{1,9} = 0.80$, $P = 0.371$), red-bellied woodpeckers (*Melanerpes carolinus* L.) ($\chi^2_{1,9} = 0.80$, $P = 0.371$), tree swallows (*Tachycineta bicolor* Vieillot) ($\chi^2_{1,9} = 0.80$, $P = 0.371$), tufted titmice (*Baeolophus bicolor* L.) ($\chi^2_{1,9} = 0.00$, $P = 1.000$), and white-breasted nuthatches (*Sitta carolinensis* Latham) ($\chi^2_{1,9} = 0.80$, $P = 0.371$) were similar between channel sides (Table 5). There was no interaction between year and side for any species or group ($P \geq 0.118$). Over both years, cavity characteristics had an effect on native cavity bird abundance ($Y = 2.095 - 0.788$[volume] + 1.566 [breadth]; $F_{2, 37} = 5.65$, $P = 0.007$, $R^2 = 0.234$, Akaike's information criterion [AIC] = -41.39) and total cavity bird abundance ($Y = -1.363 + 1.324$[height from ground]; $F_{1, 38} = 9.54$, $P = 0.004$, $R^2 = 0.202$, AIC = -15.82).

DISCUSSION

Habitat for cavity-nesting birds was better on the back channel side than on the navigational channel side, due to the greater number of cavities, cavity trees, and potentially basal area found on the back channel side. Cavity tree d.b.h. was higher on the back channel side, which indicates that the trees will remain standing longer and provide a greater variety of cavity sizes, allowing for greater species richness (DeGraaf and Shigo 1985, Newton 1994). Mannan et al. (1980) found that cavity-nesting bird density was positively correlated with d.b.h. of snags. Rosenberg et al. (1988) found that snags with larger diameters were used more often by foraging birds than were smaller snags.

The average Maser decay class (Maser et al. 1979) of the cavity trees in 2001 was lower on the back channel side than the navigational side. This finding signifies that the cavity trees on the back channel side were generally in better health (Maser et al. 1979), which could result in cavities that are more stable for nesting, and should provide better-quality habitat for a longer time (Kahler and Anderson 2006). Tree resistance to decay is partly dependent on tree species (DeGraaf and Shigo 1985, Maser et al. 1979). Sycamore and black locust trees are known for their longevity, unlike silver maple (Fowells 1965) and box elder (Manion 1981). The heartwood of sycamore is considered nonresistant to natural decay (Sheffer and Cowling 1966). It is a good cavity tree because it is susceptible to few serious diseases and is regarded as wind-firm (Fowells 1965). More silver maple and box elder cavity trees were found than sycamore and black locust, suggesting that most cavity trees on the islands are susceptible to early decomposition. However, a good variety of decay-resistant and non-decay-resistant trees will ensure adequate cavity resources over time.

There was not an overwhelming loss of cavity trees from 2000 to 2001. In the original 20 plots, there was a loss of 12 cavity trees and recruitment of 11 cavity trees between 2000 and 2001. Two of the 12 trees contained cavities that were no longer considered suitable in 2001 and 10 fell due to windthrow or erosion. Overall, there was a net loss of one cavity tree between 2000 (171 cavity trees) and 2001 (170 cavity trees), or a 0.6 percent loss of available cavity trees within the 20 original plots. Although not a significant loss, a net loss of cavity trees from one year to the next could present a problem for cavity-nesting birds over time if the rate of loss increases.

Investigating the density of cavity trees can assist in predicting populations of cavity-nesting birds (McComb and Muller 1983, Sedgwick and Knopf 1992). The combination of losing cavity trees to unavailability and erosion could create a habitat-limiting situation for cavity-nesting birds. If this trend continues, the population of cavity-nesting birds could decrease in response to fewer cavities. Availability of cavity trees is often considered a major limiting factor for a population of cavity-nesters (Brush 1983, von Haartman 1957, Zarnowitz and Manuwal 1985), especially if the quality of the cavities is low (Carlson et al. 1998).

Although the habitat appeared more favorable on the back channel side for cavity-nesters, channel side did not appear to have a strong effect on the distribution of cavity-nesting birds. Generally, the greater number of cavity trees and cavities provides the necessary environment for native cavity species to reproduce (McComb and Muller 1983, Newton 1994, Sedgwick and Knopf 1990). Furthermore, most cavities found on the back channel side were limb holes, which can have higher use by cavity-nesting birds than other cavity types (Carlson et al. 1998).

Because we found that the height of cavities from the ground was higher on the back channel side, it is possible that the cavity-nesting birds did not select cavities that high. However, this scenario is unlikely because a positive relation was found between cavity height from ground and total cavity-nesting birds. Carlson et al. (1998) found that cavity height above ground was the most important cavity characteristic connected with use by cavity-nesting birds, and that used cavities were located higher from the ground than unused cavities. Sedgwick and Knopf (1990) also found that most cavity-nesting bird species used cavities at greater heights. Li and Martin (1991) found that nest success was greater for species nesting in higher cavities, and suggested that results could be due to depredation.

Cavity breadth was lower on the back channel side, which might have deterred cavity-nesting birds from using some of the cavities there, although a positive relation was found between cavity breadth and native cavity-nesting bird abundance. Inner cavity circumference, similar to cavity breadth, also was smaller for used cavities (Carlson et al. 1998). Entrance size, entrance width, inside height, and volume were other cavity characteristics associated with native cavity-nesting bird abundance. Carlson et al. (1998) found that used cavities were associated with entrance size, volume, inner cavity circumference, and wall thickness. Sedgwick and Knopf (1990) found that cavity-nesting species selected cavities with entrance diameters that differed between species. European starlings and northern flickers selected cavities with larger diameters than did black-capped chickadees (*Poecile atricapillus* L.) and house wrens (Sedgwick and Knopf 1990). Despite these associations, cavity dimensions, with the exception of cavity breadth, were similar between channel sides and thus do not necessarily explain the distribution of cavity-nesting birds on the islands.

Primary cavity-nesters, like downy woodpeckers, would have been affected not by the cavities already created but more likely by tree characteristics such as d.b.h., which could explain why their abundance was higher on the back channel side. Runde and Capen (1987) found that downy and hairy woodpecker nests were associated with live trees, whereas black-capped chickadees selected well-decayed snags. Some cavity-nesting birds on the islands might have been nesting on the back channel side but foraging on the navigational side. Bird species may be able to obtain more of their resources, such as food and shelter, where the habitat is more diverse (Penhollow and Stauffer 2000). Habitat diversity was lower on the back channel side probably because that side mostly consisted of mature hardwood areas, whereas the navigational side also contained some immature hardwood areas. European starlings are known for their generalist behavior in choosing habitat for nesting (Ehrlich et al. 1988) and might not select one channel side over another for nesting. Another factor influencing cavity-bird distribution is territory size. Rendell and Robertson (1989) suggested that the avoidance of many tree cavities resulted from intraspecific territoriality. Furthermore, habitat quality should be measured in terms not only of density, but also of survival and reproductive potential (Van Horne 1983, Vickery et al. 1992); however, density can be a suitable predictor of habitat quality if the spatial scale is not too coarse (Maurer 1986).

Despite differences in cavity characteristics between channel sides, it is possible that cavity abundance is not actually limiting to cavity-nesters on the navigational side. Because use of cavities was not determined, we cannot ascertain if cavities are a limiting factor for cavity-nesting populations on navigational channels of the Ohio River. However, nest box use on a subset of the islands used in this study, suggests no difference in use between navigational and back channel sides (Sacilotto and Anderson 2005), but evidence suggests that habitat is more suitable for cavity-nesting species on the back channel side. We believe that the lack of significant differences in cavity-nesting songbird abundance is related to their strong territoriality (Rendell and Robertson 1989), thus limiting their densities, as back channels were more heavily used by waterfowl, turtles, and aquatic mammals (Zadnik et al. 2009). Nonetheless, islands on the Ohio River are important to cavity-nesting birds and other wildlife.

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HERPETOFAUNAL ABUNDANCE IN FORESTED EDGE AND INTERIOR LOCATIONS OF WEST VIRGINIA

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Abstract.—The diversity of forest types in the Central Appalachians provides important habitat for amphibians and reptiles. As development continues, increased fragmentation is evident on the landscape. The objectives of our study were to determine the influence of location within a forest (edge or interior) and landscape position (riparian and upland) on West Virginia herpetofaunal species abundance and diversity. Using drift fence arrays, we captured individuals from 17 amphibian species and 6 reptilian species during 43,144 trap-nights. Eastern red-backed salamanders (*Plethodon cinereus* Green) (30 percent of captures), wood frogs (*Lithobates sylvaticus* LeConte) (17 percent), eastern American toads (*Anaxyrus a. americanus* Holbrook) (16 percent), and red-spotted newts (efts) (*Notophthalmus v. viridescens* Rafinesque) (12 percent) were most commonly captured. Eastern American toads were more abundant in upland than riparian areas, and eastern red-backed salamanders, wood frogs and red-spotted newts were captured equally in riparian and upland areas. Wood frogs and red-spotted newts were encountered more frequently in interior than edge locations; red-backed salamanders and eastern American toads were captured equally in interior and edge locations. Northern slimy salamanders (*P. glutinosus* Green) were more abundant in upland than riparian areas and also were more abundant in interior than edge locations. Species richness and diversity were not different between locations or landscape position. Our results suggest that edges adversely impact abundance of some, but not all, species of amphibians and these influences are not dependent on the landscape position.

INTRODUCTION

The distribution and habitat association of terrestrial and aquatic amphibians and reptiles are poorly known compared to those of other forest vertebrates (Drost and Fellers 1996, Dunson et al. 1992). Therefore, research that measures herpetofaunal population changes among habitats is needed to conserve local and global native species richness and composition (Busby and Parmelee 1996, DeGraaf and Rudis 1990, Millar et al. 1990, Phillips 1990, Probst and Crow 1991). Herpetofaunal species are integral components of ecosystems and often compose the greatest vertebrate biomass in an area (Burton and Likens 1975, Vitt et al. 1990). Herpetofauna also serve as both predator and prey to numerous organisms, including small mammals, birds, and even other herpetofauna. Therefore, evaluating herpetofaunal population status among various habitat types and conditions is critical for the proper management of these species (Blaustein and Wake 1990, Burton and Likens 1975).

During the last several decades, awareness of the importance of herpetofaunal species and their habitats has grown as documentation of amphibian and reptile declines has increased (Blaustein 1994, Blaustein and Wake 1990, Gibbons et al. 2000, Pechmann and Wilbur 1994, Pechmann et al. 1991, Wake 1991). Reasons for declines include deforestation, habitat fragmentation, and exploitation (Grialou et al. 2000, Kuusipalo and Kangas 1994, Ward et al. 2008). Although the process of forest

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fragmentation may create only temporary effects within a forested landscape, the effects of edge remain largely unstudied for amphibians and reptiles (DeGraaf and Yamasaki 1992, Windmiller et al. 2008). Populations of several herpetofaunal species depend on the quantity and quality of the microhabitat they occupy; as a result, many herpetofaunal species may be negatively impacted by the changes in structural habitat characteristic of management-induced forest edges (deMaynadier and Hunter 1998).

Throughout the Appalachian region, the impacts of logging, mining, and other land use practices are evident throughout the landscape, yet the influence of such operations remains unclear for existing native biota (Mitchell et al. 1999, Petranka et al. 1994). Since the late 19th and early 20th centuries, extensive logging and frequent fires have occurred throughout the upland forest region of the Appalachians, leaving present-day forests in a mosaic of second- and third-growth communities (Stephenson 1993). Therefore, it is imperative that research be conducted to evaluate and identify the significance of habitat disturbances and edge effects on native biota. The objectives of our study were to determine the influence of location (edge and interior) and habitat (riparian and upland) on herpetofaunal species abundance, richness, and diversity.

STUDY AREA

We conducted our study on three tracts (Cantonment [378 ha], Briery Mountain [423 ha], and Pringle [854 ha]) that form the 1,655-ha Camp Dawson Collective Training Area (CDCTA) in Preston County, West Virginia (Osbourne et al. 2002). The CDCTA, located in north-central West Virginia, has served as a military training site for the West Virginia Army National Guard since 1909.

Elevations on Camp Dawson range from 122-853 m. During the last two centuries logging, strip and deep mining for coal, and farming have affected the study area (Osbourne et al. 2002). In addition to military training, natural resource management is a top priority, with a special emphasis on protection of state rare plants and animals, management of game species and hunting, and management to achieve a diversity of landscape components (Anderson et al. 2004). Eighty-one percent of the area was covered by mixed mesophytic forests, successional forests of low-elevation plateaus, or mature or successional floodplain forests (Vanderhorst 2002). The base had 1,085 ha of upland forested area and 313 ha of forested riparian area (Osbourne et al. 2005). Forest interior (>100 m from the forest edge) made up 749 ha and forest edge, 649 ha; the remaining 267 ha was classified as open areas (Osbourne et al. 2005).

METHODS

Trapping

We collected herpetofauna from standard cross-shaped pitfall arrays with a 19-L bucket in the middle and at the end of each 7.5-m silt fence length (Bury and Corn 1987, Greenberg et al. 1994, Mengak and Guynn 1987, Osbourne et al. 2005). We buried silt fencing 3-4 cm deep and placed buckets flush with the ground. A small amount of water (0-5 cm) was kept in the bottom of each bucket to provide a dry substrate for some rodents, but reduce the possibility of escape and desiccation of captured herpetofauna (Spurgeon and Anderson 2002). Double-ended funnel traps, constructed from aluminum hardware cloth and plastic funnels, were installed at each array with one trap along each side of a fence section to target snakes (Bury and Corn 1987, Spurgeon and Anderson 2002). The body of the funnel trap was 46 cm long and each funnel had an outside diameter of 10 cm and an inner-opening diameter of 5 cm. Traps were held in place by clearing away all debris and making a shallow depression in the soil for them to rest on. Rocks, sticks, and soil were packed against the traps and between the traps and fence to stabilize the traps and prevent organisms from passing through the gaps.

We located all arrays in forested areas. We determined locations for arrays by classifying sites as riparian or upland areas and interior or edge array locations. We considered riparian areas to be characterized by riparian vegetation and located <100 m from a permanent water body; upland habitat was anything not fitting the description of riparian habitat (Laerm et al. 1997, Osbourne et al. 2005). We defined edge locations as arrays <100 m from the edge of a forest, and interior locations were areas $\geq$100 m from the edge of a forest.

From July 5 to October 27, 2000, we collected individuals from 13 arrays distributed as 6 riparian, 7 upland, 8 edge, and 5 interior (5 riparian-edge, 1 riparian-interior, 3 upland-edge, and 4 upland-interior). During the second year of sampling (April 6 to October 29, 2001), we added 7 new arrays for a total of 20. The distribution of our arrays among treatments was 10 riparian, 10 upland, 11 edge, and 9 interior sites (6 riparian-edge, 4 riparian-interior, 5 upland-edge, and 5 upland-interior sites). Pitfall arrays were continuously open and we checked them once every 24 to 72 hours for captures. We determined species for all captures and live individuals were released onsite (Osbourne et al. 2005, Spurgeon and Anderson 2002). Methods for marking individuals were modified from Martof (1953), Brown and Parker (1976), and Cagle (1939). Small fingernail clippers were used to clip amphibians' toes at an angle and the digit removed was recorded. Antibacterial cream was applied to the digit to prevent infection. Ventral scale clipping on snakes was performed with surgical scissors and the number of scales from the cloacal vent was recorded for identification (Brown and Parker 1976). Turtle shells were notched with pliers and the notch location was recorded.

Pitfall Array Characterization

Using the center of each pitfall array as a reference point, we randomly established five 1 m by 1 m plots, located within a 10-m radius around the pitfall array, in which habitat variables were measured (deMaynadier and Hunter 1998). In each of these plots, length, width, and height measurements were taken on all coarse woody debris and rocks that were present so volumes could be calculated. Within the 1 m by 1m grid, we visually estimated the percentage of herbaceous ground cover (absolute value) (Daubenmire 1968) and measured percentage of canopy closure with a spherical densiometer. From the reference point, we used a 10-factor wedge prism to obtain basal area (m^2/ha) of surrounding trees (Avery and Burkhart 1983).

Data Analyses

We calculated relative abundance of amphibians and reptiles for each trapping array by using a standardized catch-per-unit effort measurement (CPUE) of captures/100 trap nights (Bury and Corn 1987, McComb et al. 1993, Osbourne et al. 2005). Marked individuals were not included in abundance estimates because they had already been counted when initially captured. The experimental unit was the pitfall array, and we chose CPUE because it provides a relative measure of capture rate that can easily be compared between treatments. We compared relative abundance among treatments for all amphibians and reptiles combined and individually for each species representing ≥1 percent of captures (Osbourne et al. 2005). We also compared species richness (number of species/100 trap nights) and Shannon Diversity Index (diversity index/100 trap nights) among treatments to detect any variation in the composition of the herpetofaunal community (Krebs 1999, Krohne 1998).

We compared total relative abundance, relative abundance per species, richness, and diversity between riparian and upland habitats and between edge and interior by using a completely randomized block analysis of variance (ANOVA) model (Osbourne et al. 2005). Our independent variables were habitat (upland or riparian) and location (interior or edge), and our blocked variables were year and tract of land. We tested normality assumptions with a univariate procedure (PROC UNIVARIATE) (SAS Institute, Cary, NC) and homogeneity of variance (HOV) assumptions with Bartlett's test. We rank transformed species richness and Shannon diversity because we were unable to fit normality and HOV assumptions (Conover and Iman 1981). We used square-root and quarter-root transformations on total relative abundance and relative abundance of individual species that met normality assumptions when transformed (Dowdy and Wearden 1991, Zar 1999). We analyzed species with low capture rates and many zero values at individual trapping arrays by using a generalized linear Poisson regression model (PROC GENMOD) (SAS Institute). Abundance of northern red salamanders (*Pseudotriton r. ruber* Latreille) was not analyzed because they were not captured in any riparian arrays, and the Poisson model could not fit a curve for this species.

We used the same ANOVA model and similar procedures as in the herpetofauna relative abundance comparison to determine any significance in mean values of habitat variables measured at pitfall arrays. Least square means was used to determine where differences occurred when there were habitat and location interactions for pitfall array habitat variables (Krebs 1999). All tests were considered significant at alpha = 0.05.

RESULTS

Habitat and Edge Effects on Herpetofauna

Total captures from pitfalls in this study were 858 individuals from 23 species (17 amphibian and 6 reptilian species) in 43,144 trap-nights (Table 1). There were 11 species that each represented ≥1 percent of captures.

Mean CPUE for total amphibian and reptile captures, species richness, and Shannon diversity all were similar between habitat types (Table 2) and locations (Table 3). We found no interaction between habitat and location for total CPUE ($F_{1, 26} = 0.62$, $P = 0.439$), species richness ($F_{1, 26} < 0.01$, $P = 0.957$), or diversity ($F_{1, 26} = 0.56$, $P = 0.462$).

Of the species that fit normal curves, eastern American toads (*Anaxyrus a. americanus* Holbrook) were more abundant in upland than riparian habitats; eastern red-backed salamanders (*Plethodon cinereus* Green), wood frogs (*Lithobates sylvaticus* LeConte), and red-spotted newts (efts) (*Notophthalmus v. viridescens* Rafinesque) were encountered equally in riparian and upland habitats (Table 2). Wood frogs and red-spotted newts were captured more frequently in interior than edge locations, and red-backed salamanders and eastern American toads were encountered equally in

Table1.—Number of individuals for amphibian and reptilian species captured in pitfall traps on the Camp Dawson Collective Training Area in Preston County, West Virginia during 2000 and 2001

	Number of individuals captured			
Species	2000	2001	Total	Percentage of total captures
Eastern red-backed salamanders (*Plethodon cinereus* Green)	144	114	258	30
Wood frogs (*Lithobates sylvaticus* LeConte)	49	100	149	17
Eastern American toads (*Anaxyrus a. americanus* Holbrook)	45	93	138	16
Red-spotted newts (efts) (*Notophthalmus v. viridescens* Rafinesque)	26	80	106	12
Northern green frogs (*L. clamitans melanota* Rafinesque)	8	46	54	6
Northern slimy salamanders (*Plethodon glutinosus* Green)	22	15	37	4
Allegheny Mountain dusky salamanders (*Desmognathus ochrophaeus* Cope)	9	20	29	3
Northern red salamanders (*Pseudotriton r. ruber* Latreille)	2	20	22	3
Pickerel frogs (*Lithobates palustris* LeConte)	9	8	17	2
Four-toed salamanders (*Hemidactylium scutatum* Schlegel)	10	6	16	2
Eastern gartersnakes (*Thamnophis s. sirtalis* Linnaeus)	4	3	7	1
Northern spring salamanders (*Gyrinophilus p. porphyriticus* Green)	1	3	4	<1
Northern dusky salamanders (*Desmognathus f. fuscus* Rafinesque)	1	2	3	<1
Appalachian seal salamanders (*Desmognathus monticola* Dunn)	3	0	3	<1
Eastern snapping turtles (*Chelydra s. serpentina* Linnaeus)	2	1	3	<1
Fowler’s toads (*Anaxyrus fowleri* Hinckley)	2	0	2	<1
Gray tree frogs (*Hyla versicolor* LeConte /*Hyla chrysoscelis Cope*)	2	0	2	<1
Northern ring-necked snakes (*Diadophis punctatus edwardsii* Merrem)	2	0	2	<1
Eastern milksnakes (*Lampropeltis t. triangulum* LaCépède)	0	2	2	<1
Northern two-lined salamanders (*Eurycea b. bislineata* Green)	0	1	1	<1
Spring peepers (*Pseudacris crucifer* Wied-Neuwied)	1	0	1	<1
Smooth greensnakes (*Opheodrys vernalis* Harlan)	1	0	1	<1
Eastern ratsnakes (*Pantherophis alleghaniensis* Holbrook)	1	0	1	<1

interior and edge locations (Table 3). No interactions were produced between habitat type and location for individual species capture rates ($F_{1,\,26} \leq 0.76$, $P \geq 0.390$).

Northern slimy salamanders were more abundant in upland than riparian habitats ($\chi^2 = 5.65$, $P = 0.017$) and were more abundant in interior than edge locations ($\chi^2 = 4.74$, $P = 0.030$). All other species analyzed with the generalized Poisson regression showed similar relative abundance in upland and riparian habitats (Table 4) and in interior and edge trapping locations (Table 5). No interactions were observed between habitat and trapping location for individual species relative abundances ($\chi^2 \leq 0.91$, $P \geq 0.340$).

Table 2.—Average relative abundance in captures/100 trap nights (CPUE), species richness, and Shannon Diversity Index for amphibian species captured in pitfall traps in riparian (2000: n=6; 2001: n=10) and upland (2000: n=7; 2001: n=10) habitats on the Camp Dawson Collective Training Area in Preston County, West Virginia during 2000 and 2001

	Riparian		Upland			
Species or index	$\bar{x}$	SE	$\bar{x}$	SE	$F_{1,26}$	P
CPUE						
Eastern red-backed salamanders (*Plethodon cinereus* Green)	0.41	0.20	1.30	0.50	1.64	0.211
Wood frogs (*Lithobates sylvaticus* LeConte)	0.44	0.11	0.29	0.08	3.38	0.077
Eastern American toads (*Anaxyrus americanus* Holbrook)	0.22	0.05	0.45	0.12	4.91	0.036
Red-spotted newts (efts) (*Notophthalmus v. viridescens* Rafinesque)	0.20	0.08	0.29	0.08	0.01	0.918
All species combined	1.75	0.35	2.90	0.65	1.21	0.282
Species richness/100 trapnights	0.48	0.07	0.54	0.10	0.02	0.903
Shannon diversity/100 trapnights	0.11	0.02	0.11	0.01	0.26	0.615

Table 3.—Average relative abundance in captures/100 trap nights (CPUE), species richness, and Shannon Diversity Index for amphibian species captured in pitfall traps in edge (2000: n=8; 2001: n=11) and interior (2000: n=5; 2001: n=9) locations on the Camp Dawson Collective Training Area in Preston County, West Virginia during 2000 and 2001

	Edge		Interior			
Species or index	$\bar{x}$	SE	$\bar{x}$	SE	$F_{1,26}$	P
CPUE						
Eastern red-backed salamanders (*Plethodon cinereus* Green)	0.86	0.42	0.88	0.40	0.50	0.487
Wood frogs (*Lithobates sylvaticus* LeConte)	0.25	0.07	0.53	0.11	9.49	0.005
Eastern American toads (*Anaxyrus americanus* Holbrook)	0.32	0.07	0.37	0.13	1.78	0.194
Red-spotted newts (eft) (*Notophthalmus v. viridescens* Rafinesque)	0.11	0.04	0.43	0.11	5.50	0.027
All species combined	2.10	0.55	2.73	0.53	1.57	0.222
Species richness/100 trapnights	0.53	0.10	0.49	0.06	0.40	0.532
Shannon diversity/100 trapnights	0.11	0.02	0.12	0.01	0.77	0.387

Table 4.—Average relative abundance in captures/100 trap nights (CPUE) of amphibian and reptilian species captured in pitfall traps in riparian (2000: n=6; 2001: n=10) and upland (2000: n=7; 2001: n=10) habitats on the Camp Dawson Collective Training Area in Preston County, West Virginia during 2000 and 2001

	Riparian		Upland			
Species	$\bar{x}$	SE		SE	$\chi^2_{1,26}$	P
Northern green frogs (*Lithobates clamitans melanota* Rafinesque)	0.15	0.06	0.09	0.06	1.32	0.250
Northern slimy salamanders (*Plethodon glutinosus* Green)	0.03	0.02	0.20	0.07	5.65	0.017
Allegheny Mountain dusky salamanders (*Desmognathus ochrophaeus* Cope 1859)	0.09	0.04	0.05	0.05	0.07	0.785
Northern red salamanders (*Pseudotriton r. ruber* Latreille)	0.00	0.00	0.09	0.06	NA	NA
Pickerel frogs (*Lithobates palustris* LeConte)	0.07	0.04	0.03	0.01	1.68	0.195
Four-toed salamanders (*Hemidactylium scutatum* Schlegel)	0.03	0.01	0.07	0.04	0.11	0.737
Eastern gartersnake (*Thamnophis s. sirtalis* Linnaeus)	0.02	0.01	0.03	0.02	<0.01	0.999

Table 5.—Average relative abundance in captures/100 trap nights (CPUE) of amphibian and reptilian species captured in pitfall traps in edge (2000: n=8; 2001: n=11) and interior (2000: n=5; 2001: n=9) locations on the Camp Dawson Collective Training Area in Preston County, West Virginia during 2000 and 2001

	Edge		Interior			
Species	$\bar{x}$	SE	$\bar{x}$	SE	$\chi^2_{1,26}$	*P*
Northern green frogs (*Lithobates clamitans melanota* Rafinesque)	0.13	0.06	0.11	0.08	0.80	0.371
Northern slimy salamanders (*Plethodon glutinosus* Green)	0.06	0.04	0.20	0.06	4.74	0.030
Allegheny Mountain dusky salamanders (*Desmognathus ochrophaeus Cope 1859*)	0.11	0.05	0.01	0.01	2.99	0.084
Northern red salamanders (*Pseudotriton r. ruber* Latreille)	0.06	0.06	0.03	0.01	NA	NA
Pickerel frogs (*Lithobates palustris* LeConte)	0.07	0.03	0.02	0.01	0.58	0.446
Four-toed salamander (*Hemidactylium scutatum* Schlegel)	0.03	0.01	0.07	0.05	0.10	0.746
Eastern gartersnake (*Thamnophis s. sirtalis* Linnaeus)	0.02	0.01	0.03	0.02	<0.01	0.999

Table 6.—Means and standard errors for habitat characteristics measured in two habitat and two treatment groups in which pitfall arrays were established on the Camp Dawson Collective Training Area in Preston County, West Virginia during 2000 and 2001

	Habitat				Treatment			
	Upland		Riparian		Edge		Interior	
Habitat characteristic	$\bar{x}$	SE	$\bar{x}$	SE	$\bar{x}$	SE	$\bar{x}$	SE
Volume coarse woody debris (cm^3/m^2)	324.84	143.22	159.7	88.36	264.73	165.07	275.73	101.75
Rock volume (cm^3/m^2)	372.26	175.57	1,705.27	1,141.98	279.99	165.07	1,445.72	843.88
Canopy closure (percent)	61.36	7.17	76.12	8.1	48.26	7.43	87.4	6.38
Herbaceous ground cover (percent)	54.17	4.77	69.48	6.38	67.85	5.15	49.21	5.48
Basal area (m^2/ha)	13.99	2.11	14.54	2.41	8.78	1.84	20.5	2.26

Habitat Characteristics of Pitfall Arrays

Mean volume of coarse woody debris was similar between upland and riparian habitats ($F_{1,26}$ = 0.06, P = 0.813), as were mean canopy closure ($F_{1,26}$ = 1.67, P = 0.202), mean herbaceous ground cover ($F_{1,26}$ = 0.45, P = 0.504), and mean basal area (m^2/ha) ($F_{1,26}$ = 0.24, P = 0.628); however, mean rock volume was greater in riparian than upland habitats ($F_{1,26}$ = 7.01, P = 0.011) (Table 6). Mean volume of coarse woody debris ($F_{1,26}$ = 1.36, P = 0.248) and herbaceous ground cover ($F_{1,26}$ = 1.78, P = 0.188) were similar between edge and interior treatments; however, mean rock volume was greater in interior than edge treatments ($F_{1,26}$ = 5.86, P = 0.019), as were canopy closure ($F_{1,26}$ = 11.92, P = 0.001) and mean basal area ($F_{1,26}$ = 13.70, $P < 0.001$) (Table 6). There was no habitat-treatment interaction for coarse woody debris ($F_{1,26}$ = 1.61, P = 0.211), canopy closure ($F_{1,26}$ = 0.21, P = 0.649), herbaceous ground cover ($F_{1,26}$ = 0.44, P = 0.508), or basal area ($F_{1,26}$ = 0.02, P = 0.895). There was a habitat-treatment interaction for mean rock volume ($F_{1, 26}$ = 5.23, P = 0.026).

DISCUSSION

Edge and Interior

Abundance of wood frogs and of red-spotted newts were lower in edges than in interior locations within our study area. Wood frogs generally breed in vernal pools surrounded by mature forests and are susceptible to habitat fragmentation (Windmiller et al. 2008). They are most commonly found in moist, deciduous forests with well-developed leaf litter (Green and Pauley 1987). Although others have found that red-spotted newts were less closely associated with forested, interior sites than other salamander species (de Maynadier and Hunter 1998), we found that capture rates were higher at interior arrays. This difference is likely due to differences in habitat variables between the two studies. Our interior arrays had more rock volume, greater canopy closure, and more basal area compared to edges. An abundance of trees, which leads to high canopy cover, is important for forest-dwelling amphibians because it helps to maintain a deep litter layer and moist microclimate. Moreover, the presence of these variables appears to be more important than the absence of a coarse woody debris effect.

In our study, edge did not appear to influence red-backed salamanders, eastern American toads, northern green frogs (*Lithobates clamitans melanota* Latreille), Allegheny Mountain dusky salamanders (*Desmognathus ochrophaeus* Cope), pickerel frogs (*L. palustris* LeConte), four-toed salamanders

(*Hemidactylium scutatum* Schlegel), eastern gartersnakes (*Thamnophis s. sirtalis* Linnaeus), and overall species richness and diversity. Others have found that red-backed salamanders are most abundant in mature forests with deep soils, abundant litter, and scattered logs and rocks (Burger 1935, Green and Pauley 1987, Heatwole 1962). However, capture rates of red-backed salamanders and many other salamander species must be interpreted with caution because subsurface habitat use is so prevalent (Nagel 1977, Petranka 1998, Test and Heatwole 1962). Nonetheless, pitfalls are adept at capturing these underground-dwelling species as they emerge at night to forage. On our study area, the volume of coarse woody debris and herbaceous ground cover was similar between edge and interior locations, which likely contributed to the similar relative abundance estimates; similar volumes of coarse woody debris between sites appeared particularly important for red-backed salamanders.

Eastern American toads are generalist species found in various forested and open cover types (Green and Pauley 1987, Knutson et al. 1999). Therefore, it is not surprising that edge had little influence on the species. However, some have found that logging can affect American toad metamorphs, which may avoid open-canopy cover (deMaynadier and Hunter 1998, Rothermel and Semlitsch 2002). On our study area, canopy cover was 37 percent higher in interior areas (85 percent) compared to edges (48 percent), but most wetlands on the study area are located in edges. Thus, metamorphs dispersing from wetlands on Camp Dawson have to travel through open areas.

An area not classified as edge by our definition still may have undergone disturbance. Forested areas on the study site have been logged and some were even mined or farmed in the past, like much of the Central Appalachians; consequently, abundance has been reduced even in the interior areas (Perkins and Hunter 2006). Mining in particular has potentially disrupted dispersal corridors and movements among habitat patches and restoration of these areas should serve to reduce edge effects (Anderson et al. 2004). However, we believe our criterion of a 100-m distance from edge was sufficient because road effects on salamanders may extend only 35 m, according to research involving both gravel and paved roads (Semlitsch et al. 2007). Moreover, more-interior areas (60-80 m) may actually harbor fewer salamanders than the 35- to 60-m distances (Marsh and Beckman 2004, Semlitsch et al. 2007), indicating that some limited nearby disturbance may not be completely detrimental to woodland salamander populations.

Overall, edges had little influence on relative abundance of amphibians in our study area. We believe this finding is due to relatively low capture rates for most species and similar disturbance regimes throughout the interior and edges. In other areas, edges may have a more significant impact if disturbance regimes are more pronounced in edges compared to interior areas. Thus, we hypothesize that landscape-level disturbance regimes override localized edge effects for amphibians.

Riparian and Upland Habitats

Herpetofaunal community structure differed little between the upland and riparian areas. Slimy salamanders and eastern American toads were the only species we found to differ in abundance between upland and riparian areas; they were more abundant in uplands than riparian zones. Abundant cover objects and moist microclimates within deciduous forests are preferred areas for slimy salamanders (Grover 1998). Coarse woody debris, canopy closure, herbaceous ground cover, and basal area were similar in riparian and upland areas and only rock volume, which was five times greater in riparian than upland areas, differed. It is likely that microsite differences–rock volume, an unmeasured variable, or possibly the synergistic effect of multiple differences (albeit nonsignificant)–influenced relative abundance overall.

Eastern American toads, although dependent on wetlands for reproduction, are not dependent on streams and associated riparian areas for reproduction. Wetlands were primarily located in open areas adjacent to riparian sites, which were not sampled as part of this study. Some wetlands in upland areas adjacent to logging roads and other disturbed areas provided areas conducive to breeding and reproducing. Thus, the upland forested areas were likely closer to the best breeding areas, potentially explaining why uplands had more toads. All other species analyzed, including green frogs, Allegheny Mountain dusky salamanders, pickerel frogs, four-toed salamanders, eastern gartersnakes, red-backed salamanders, and red-spotted newts, were nonsignificant, although in several cases abundance was two to three times higher in one habitat or the other. Overall capture rates were relatively low for most of these species.

Although we captured some stream salamanders (e.g., Allegheny Mountain dusky salamanders), we did not capture many and thus did not analyze these species, which contributed to our finding of few overall differences. We would have expected more stream and streamside salamanders in riparian areas, but these species often do not leave headwater streambeds and thus were likely not picked up with our sampling regime.

CONCLUSIONS

Overall, all forested areas—riparian and upland, edge and interior—are crucial for maintaining the herpetofaunal community in the Central Appalachians. Even though we found few differences between edges and forested interior or between wooded riparian and upland areas, we do not suggest that these various areas are interchangeable. For example, upland habitat cannot replace destroyed riparian habitat, and riparian habitat cannot replace upland habitat (Osbourne et al. 2005). Thus, both still need to be maintained. Similar interpretations apply to edges and interiors. It is important for future studies to evaluate habitat use from a landscape perspective in addition to localized effects. Although we found some differences in relative abundance and habitat characteristics between upland and riparian areas and edge and interior locations, the results are not always intuitive. Interactions among habitat types such as forests and wetlands appear to be important sources of unmeasured variation in this study. Evaluating these synergies and interactions will strengthen future research efforts aimed at understanding herpetofaunal habitat use and edge effect in forested environments.

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SURVIVAL RATES OF FEMALE WHITE-TAILED DEER ON AN INDUSTRIAL FOREST FOLLOWING A DECLINE IN POPULATION DENSITY

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Abstract.—With white-tailed deer (*Odocoileus virginianus*) populations at historically high levels throughout many North American forests, many current management activities are aimed at reducing deer populations. However, very little information exists on the ecology of low-density white-tailed deer populations or populations that have declined in density. We examined survival and cause-specific mortality rates in a white-tailed deer population that recently experienced a substantial (>50 percent) decline in population density on an industrial forest in central West Virginia. We monitored 57 adult female deer from August 2006 to April 2008, documenting 18 mortalities. Annual survival was 0.810 (0.733–0.894), similar to results found before population decline. Annual cause-specific mortality rates were 0.119 (0.062–0.177) for anthropogenic mortality and 0.071 (0.029–0.113) for natural mortality. The increase in anthropogenic mortality likely resulted from changes in harvest regulations and access to our study area. Our results support previous work suggesting that adult survival rates in ungulates are robust to changes in population density and indicate that density-dependent mechanisms were not acting upon adult survival in this population during our study.

INTRODUCTION

White-tailed deer (*Odocoileus virginianus*) are keystone herbivores in much of North America and can influence many aspects of ecosystem dynamics (Russell et al. 2001). Although the recovery of the white-tailed deer is one of the great success stories in wildlife management, many populations are at levels impacting other aspects of the biota and are deleterious for sustained, healthy ecosystem function (Cote et al. 2004). Overabundant deer populations can affect forested ecosystems in several ways, including reducing the abundance and diversity of understory vegetation and limiting forest regeneration (Rossell et al. 2005, Russell and Fowler 2004, Tilghman 1989). These alterations to the plant community can affect other wildlife by reducing the amount of suitable habitat or forage available for insects (Allombert et al. 2005), birds (McShea et al. 1995), and small mammals (Horsley et al. 2003). Additionally, overabundant deer populations tend to be characterized by animals in poorer physical condition (Keyser et al. 2005b) with higher rates of parasite prevalence than herds at lower density (Eve and Kellogg 1977). Wildlife managers now must implement strategies that

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minimize the biological impacts of these overabundant populations (Brown et al. 2000). Attempts to reduce deer populations by using techniques such as controlled public hunts (Kilpatrick and Walter 1999, McDonald et al. 2007), small-scale removal of family groups (McNulty et al. 1997, Miller et al. 2010), contraceptive and fertility treatments (Locke et al. 2007), or other techniques have had varying degrees of success.

Relatively little information exists on how these management actions affect deer population characteristics. Density-dependent responses in home-range size (Henderson et al. 2000, Kilpatrick et al. 2001), habitat use (Kie and Bowyer 1999), and recruitment (Keyser et al. 2005a) have been observed in white-tailed deer. Studies of mule deer (*O. hemionus*) in Colorado (Bartmann et al. 1992, White and Bartmann 1998) and red deer (*Cervus elaphus*) in Europe (Clutton-Brock et al. 1987) suggest that population density also may affect fawn survival, although this pattern has not often been reported in white-tailed deer (McCullough 1979, Patterson et al. 2002). Despite this abundance of research examining the effects of population density on white-tailed deer, virtually no information exists to address whether adult survival exhibits density-dependent patterns. McCullough (1979, 1990) suggested that adult survival rates are robust to changes in population density in white-tailed deer, but little empirical evidence exists on such relations to confirm this assertion.

Understanding how population density may affect survival rates in white-tailed deer is important for developing sound natural resource management plans, particularly in forested landscapes. Our objectives were to identify patterns in adult female survival and mortality rates in a white-tailed deer population that had recently undergone a substantial reduction in population size (>50 percent). We hypothesized that adult female survival rates would be higher than those reported before population reduction because of per-capita increases in resource availability.

STUDY AREA

We conducted our study on the MeadWestvaco Wildlife and Ecosystem Research Forest (MWERF) in central Randolph County, West Virginia. The 3,413-ha site occurs in the Unglaciated Allegheny Mountain and Plateau physiographic province and ranges in elevation from 734 to 1,180 m. Average annual precipitation on the site ranges between 170 and 190 cm with an average snowfall >300 cm/year. The majority of the site was logged initially between 1916 and 1928 and at the beginning of our study comprised primarily maturing, second-growth northern hardwood-Allegheny hardwood forests (Keyser and Ford 2005). These forests were dominated by American beech (*Fagus grandifolia*), black cherry (*Prunus serotina*), sugar maple (*Acer saccharrum*), red maple (*A. rubrum*), yellow birch (*Betula alleghenisis*), and northern red oak (*Quercus rubra*). Higher-elevation areas were dominated by red spruce (*Picea rubens*) and eastern hemlock (*Tsuga canadensis*) communities. At lower elevations, other species such as American basswood (*Tilia americana*), black birch (*B. lenta*), and yellow-poplar (*Liriodendron tulipifera*) also were present. Throughout much of the area, the understory was dominated by greenbrier (*Smilax* spp.) and mountain laurel (*Kalmia latifolia*), with dense rosebay rhododendron (*Rhododendron maximum*) prevalent in riparian areas. Hay-scented fern (*Dennstaedtia punctilobula*) also was abundant throughout the understory due to excessive herbivory from historically high white-tailed deer densities (Keyser and Ford 2005). Between 2000 and 2008, more than 500 ha of forest have been harvested on the MWERF, of which 75 percent were clearcut and 25 percent were deferment cuts and marked selection cuts. Harvest units have averaged 34.7 ha since the mid-1990s, with most harvests conducted in the dormant season.

We conducted four population surveys between October 2005 and October 2007 along a predetermined 35-km survey route that provided adequate spatial coverage of the study area. We used a distance sampling approach to estimate population density (Buckland et al. 2001). Population density estimates from individual surveys ranged from 1.2/km^2 (95-percent confidence interval [CI]: 0.4 - 4.1) to 2.6/km^2 (95-percent CI: 1.1 - 5.7). Similar methods were used during four surveys conducted between August 2000 and May 2001 (Langdon 2001). Density estimates from these previous surveys ranged from 8.3/km^2 (95-percent CI: 6.8 - 10.0) to 10.7/km^2 (95-percent CI: 8.2 - 13.8) (Langdon 2001), indicating a decrease in population density of >50 percent. This decrease was most likely the result of research activities, which removed 100 animals between 2002 and the time of our study (Crimmins, unpublished data; Miller et al. 2010) and limited recruitment (B. Miller, unpublished data). Increases in coyote (*Canis latrans*) and black bear (*Ursus americanus*) populations throughout the region and locally may have limited deer recruitment, as both these predators are known to prey upon deer neonates in the central Appalachians (Vreeland et al. 2004).

METHODS

We captured deer by using modified clover traps (Clover 1954) baited with whole-kernel corn. Upon capture, we restrained and chemically immobilized deer by using an intramuscular injection of xylazine HCl at a dosage of 2.2 mg/kg body weight. Deer were aged yearling or adult by using tooth wear and replacement patterns (Severinghaus 1949). All animals in the study were adult (≥6 months old) females. Once sedated, deer were fitted with mortality-sensitive radio-collars (model M2600, Advanced Telemetry Systems, Ishanti, MN) and numbered plastic ear tags (PermaFlex 7341, National Band and Tag, Newport, KY). We administered a 50 percent intramuscular, 50 percent subcutaneous injection of yohimbine HCl as an antagonist (Wallingford et al. 1996). We released deer at the capture site and monitored them until they were ambulatory. All capture and handling methods were in accordance with the guidelines of the American Society of Mammalogists (Gannon and Sikes 2007) and the Animal Care and Use Committee of West Virginia University (ACUC #05-0706). We located deer ≥1 day each week from August 1, 2006 to April 30, 2008. We monitored status (dead/alive) from the ground using a TRX-2000S receiver (Wildlife Materials, Murphysboro, IL) and a 3-element Yagi antenna (SteppIR Antennas Inc., Bellevue, WA). When a mortality signal was detected, we immediately located the carcass and attempted to determine cause of death. We categorized death as natural (e.g., starvation, predation) or human-induced (anthropogenic).

We estimated annual survival using the Kaplan-Meier method with a staggered entry design (Pollock et al. 1989). We used a recurrent time design to evaluate survival and cause-specific mortality (Fieberg and DelGiudice 2009). We used a competing risks approach to estimate cause-specific mortality rates (anthropogenic vs. natural) by developing cumulative incidence functions for each mortality source to account for temporal changes in the risk set (Heisey and Patterson 2006). Our analyses were conducted using the R programming language (R Development Core Team 2008).

RESULTS

We monitored 57 adult female deer beginning August 1, 2006. During our study, which ended April 30, 2008, we documented 18 mortality events: 12 anthropogenic and 6 natural. Limited sample sizes prevented robust comparisons of survival within age classes; therefore, we present data pooled across age classes. Annual survival was 0.810 (0.733 - 0.894), with most mortalities occurring during fall

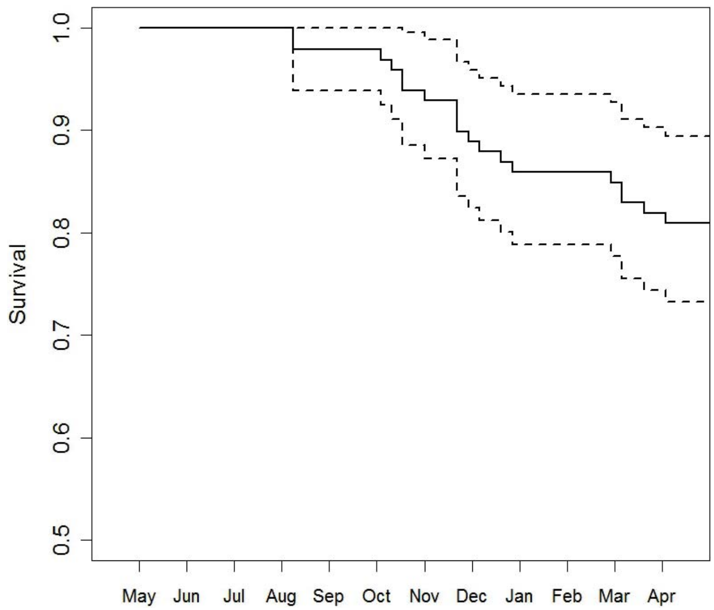

Figure 1.—Annual Kaplan-Meier survival function for white-tailed deer on the MeadWestvaco Wildlife and Ecosystem Research Forest, West Virginia, 2006-2008. Dotted lines represent 95-percent confidence intervals.

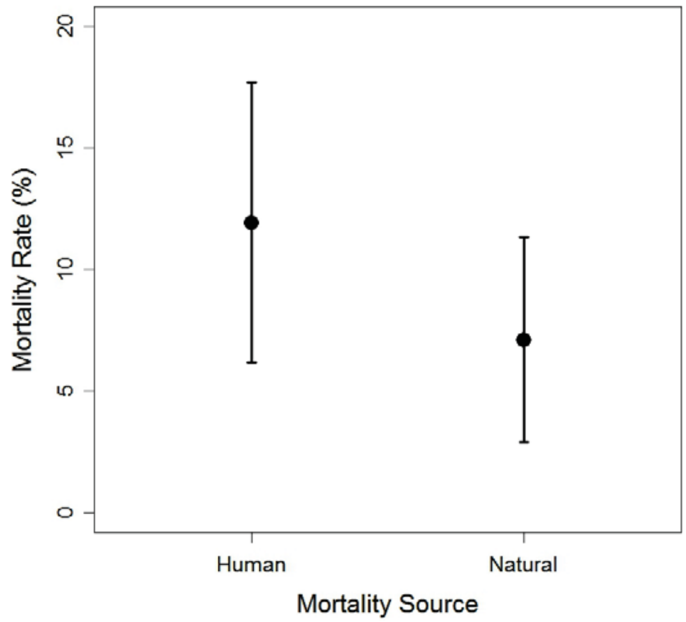

Figure 2.—Annual cause-specific mortality rates for white-tailed deer on the MeadWestvaco Wildlife and Ecosystem Research Forest, West Virginia, 2006-2008. Error bars represent 95-percent confidence limits.

(October - December) hunting season (Fig. 1). Anthropogenic (0.119) and natural (0.071) mortality rates did not differ based on overlapping 95-percent confidence intervals (Fig. 2). Natural mortalities occurred throughout the calendar year, whereas anthropogenic mortalities were concentrated in fall, coincident with hunting season. Of the 12 anthropogenic mortalities, 9 occurred during the legal hunting season (approximately October - December) and 3 occurred in the spring when the season was closed.

DISCUSSION

Our annual survival estimate (0.81, 95-percent CI 0.73–0.89) was similar to what was previously found for this population (0.88, 95-percent CI 0.84–0.93) from 1999 to 2002, when densities were substantially higher (Campbell et al. 2005). This result suggests that adult survival rates in this population are robust to changes in population density. Bartmann et al. (1992) reported that adult survival rates in mule deer (*O. hemionus hemionus*) remained constant after population reduction in Colorado despite density-dependent related changes in fawn survival; they suggested density-dependent survival responses would be observed in adults only if substantial changes in density occurred. Fowler (1981) suggested that density-dependent processes in large mammals are easier to detect the further the population is from carrying capacity. The deer population on our study area exhibited a decrease of a sufficient magnitude (>50 percent) that density-dependent related mechanisms would have been expressed (McCullough 1990). Furthermore, based on abomasal parasite counts (Campbell et al. 2005), the population was at or near nutritional carrying capacity before the decline in density. We also found an increase in overall in-utero reproductive rates from ~1.4 fawns/female from 1999 through 2001 to ~1.6 fawns/female at the time of our study (Campbell et al. 2005; Crum, unpublished data). Thus, based on the starting position of the population, the

>50-percent decrease likely represented a substantial reduction in density relative to carrying capacity. Nevertheless, we were unable to observe any significant changes in adult survival rates, suggesting that density-dependent mechanisms were not operating on this population.

Campbell et al. (2005) reported annual cause-specific mortality rates of 0.04 for anthropogenic mortality and 0.08 for natural mortality using similar analytical methods. Our estimated natural mortality rate of 0.071 was similar to that of Campbell et al. (2005), but our estimated anthropogenic mortality rate (0.119) was substantially greater. The similarity between our estimates of natural mortality is somewhat surprising, as increases in per-capita available resources resulting from decreased density would presumably lead to higher fitness (Fretwell and Lucas 1970). However, the high survival rates (>0.8) exhibited at both high and low densities suggest that resource limitations on our study site never reached a threshold where they affected adult survival (Gaillard et al. 1998). The observed increases in anthropogenic mortality could be the result of changes in human hunting pressure, as ownership changed and subsequent access to our study site increased during our study. Regardless, our results suggest that overall survival rates of adult female white-tailed deer are highly resistant to changes in population density.

The reduction in population density on our study area was likely the result of several factors, including an earlier removal of animals for research purposes over part of the study area (Miller et al. 2010), cumulative habitat degradation from two decades of overabundance that may have limited recruitment, and increased predator populations. Similarly, liberalization in harvest regulations during this time also led to an increase in the local doe harvest. During this time black bear populations increased in the area (Ryan 2009), while anecdotal evidence suggests that coyote populations also increased substantially. These predator populations may have limited recruitment by reducing fecundity and fawn survival (Kilgo et al. 2010). This multitude of factors must be considered, as we may have observed different patterns if the reduction in the deer population on our study site had resulted solely from deer management programs such as regulated harvest that would have a smaller effect on neonate survival or population growth rates.

The consistency of natural mortality rates between the two study periods suggests that other factors such as hunting pressure may influence survival rates more than population density does (Weckerly et al. 2005). In more northern latitudes, winter severity is generally thought to be one of the primary limiting factors for white-tailed deer populations (Garroway and Broders 2005). Although our study site was at latitudes not normally associated with such conditions, its relatively high elevation made the local climate more similar to northern areas with severe winters. Even though we lacked long-term data on winter severity or mast production from our study area, the relatively low observed natural mortality rates suggest that winter weather or mast failures may not have been a substantial contributing factor to adult survival rates in our population during our study period. Similarly, regional mast production estimates suggest that mast production was above average during most of our study (Ryan et al. 2009). However, it is important to note that we were unable to assess fawn survival and recruitment, which are highly susceptible to severe winter conditions.

CONCLUSIONS

Our results suggest that management actions aimed at reducing deer population density can operate under the assumption that adult female survival rates, if high prior to population reduction, will remain fairly constant after population reduction. Indeed, others have concluded that adult survival rates are extremely robust to changes in population density (McCullough 1979, White and Bartmann 1998). Our lack of an observed increase in survival rates, particularly when combined with the minimal change in natural mortality rates, suggests that population control measures may be effective at limiting population growth. Given sufficient lag-time to allow for forest regeneration, such measures may also be effective at limiting herbivory in forested regions subjected to heavy browsing pressure (Crimmins et al. 2010, Miller et al. 2009). However, the potential for increased fecundity and recruitment would need to be carefully assessed before any population control measures were taken, as these factors are more commonly thought to be density-dependent (Keyser et al. 2005a). Our results support previous research suggesting that adult survival rates in ungulates are robust to changes in population density and that density-independent factors may make important contributions to structuring population dynamics in white-tailed deer.

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AVIAN COMMUNITY RESPONSE TO HARDWOOD FOREST MANAGEMENT FOR CERULEAN WARBLERS

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Abstract.—We studied three silvicultural methods (single-tree selection, shelterwood, and deferment harvest) as potential tools to manage cerulean warbler populations on seven study areas in four Appalachian states from 2006 through 2010. We analyzed preharvest and 4 years post-harvest point count, territory mapping, and vegetation response data on plots treated with the three harvests and an unharvested reference plot to examine the broader implications of single-species management for cerulean warblers. Differences in harvest method and intensity led to differences in habitat structure and composition, with positive and negative consequences for other avian species.

The preharvest avian community was similar on all study plots. By 4 years postharvest, the four treatments had differentiated in avian composition with most change in the shelterwood and deferment harvests, primarily from positive responses of shrub-associated species such as hooded warbler, Kentucky warbler, and indigo bunting. Some forest interior species declined in all treatments (e.g., ovenbird), whereas others declined only in the heaviest harvest (e.g., worm-eating warbler). Most species remained at or near pretreatment levels in the selection harvest. Stand-specific variation in habitat and avian measures also were found, likely due to factors such as topography and within-region differences in vegetation and avian composition. A gradient of residual basal area on the harvest treatments strongly influenced the avian community. Forest management can benefit cerulean warblers as well as other avian species or assemblages of management interest. Tradeoffs among species need to be considered when selecting type of management implemented.

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CERULEAN WARBLER RESPONSE TO HARDWOOD FOREST MANAGEMENT IN THE CENTRAL APPALACHIANS

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Abstract.—Cerulean warblers (*Dendroica cerulea*), one of the fastest declining avian species in North America, are associated with heterogeneous canopies in mature hardwood forests. We examined three silvicultural methods with varying degrees of canopy disturbance (single-tree selection, shelterwood, and deferment harvests) as potential tools to manage habitat for cerulean warblers. The three harvest treatments and an unharvested reference plot were replicated on seven study areas in four Appalachian states from 2005 through 2010. The four treatments were applied randomly on each study area and harvests were implemented between the 2006 and 2007 growing seasons. We quantified cerulean warbler territory density, nest survival, and age structure on each plot in each year to examine preharvest and 4 years post-harvest response. Over all study areas, cerulean warbler territory density remained stable in unharvested plots and increased significantly in the first year post-harvest on intermediate shelterwood treatments. By 3 years post-harvest, all three harvest treatments had significantly higher territory density than unharvested plots.

Nest survival rates were influenced by study site, year, and treatment. After accounting for regional and annual differences, nests in the unharvested treatment had greater nest survival and more fledglings per successful nest than in harvested treatments. However, the number of nests found was generally higher in harvested treatments. Male age structure did not differ among treatments, but body condition was better in harvested stands. Forest management can benefit cerulean warbler density. Shelterwood harvests provide the greatest positive response of the three harvest types; however, nest success can be reduced.

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POSTER ABSTRACTS

THE EFFECT OF VARYING GLYPHOSATE AND SURFACTANT RATES ON THE CONTROL OF ORIENTAL BITTERSWEET

Terry L. Burhans, Jr. and David W. McGill[1]

Oriental bittersweet (*Celastrus orbiculatus*) is an invasive climbing, twining vine that can grow up into the forest canopy effectively inhibiting growth and light exposure on affected trees. A local landowner who treated bittersweet with various rates of a glyphosate-based herbicide claimed that higher than recommended rates of herbicide were needed to effectively control the invasive plant. Our study assessed the validity of this claim and explored the interaction of glyphosate and surfactant effects on the efficacy of bittersweet control. Our goal was to determine an ideal treatment of herbicide and surfactant rates for the effective chemical control of oriental bittersweet. Four rates of glyphosate herbicide in the form of Accord® (Dow Chemical Company) (0%, 2.5%, 5%, and 10% volume to volume) were crossed with four rates of a common surfactant (Cide-Kick® [Brewer International]; 0%, 0.5%, 1%, and 2%) to create 16 treatments. Treatments were randomly assigned to individual plants growing in the understory of two forested areas in northern West Virginia. Five replicates for each treatment at each site were separated into discrete blocks to account for any microsite variation that might be present within the treatment area. Apart from the surfactant only treatments, all glyphosate treatments were highly effective in defoliating the bittersweet stems. Our poster reports first-year results of the study and provides a glimpse of attributes that occur on this invasive species as a result of herbicide toxicity.

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COFIRING TORREFIED WOODY BIOMASS WITH COAL: A NEW CHALLENGE FOR POWER GENERATION

Juan C. Carrasco, Gloria S. Oporto, and Jingxin Wang[1]

Biomass is currently used up to 20 percent in co-combustion with coal in power plants. This feasibility has emerged as an excellent option for voluntary reduction in CO_2 emissions, however, biomass presents several limitations that are associated with its low energy density compared to fossil fuels, grinding energy, variability in moisture content, and it is microbiological degradable during storing. Today, it is possible to improve all biomass disadvantages through the torrefaction process. Preliminary results obtained in our laboratories demonstrated that red oak (*Quercus rubra* L.) can be efficiently torrefied in a fluidized bed reactor giving a yield between 0 and 60 percent corresponding to calorific values that vary between 17 and 23 MJ/kg. The experiment was performed in an inert environment with the following conditions: particle size of the raw material between 0.7 and 1.4 mm, temperature of the system between 220 ºC and 260 ºC, and the reaction time between 5 and 10 minutes. Torrefied red oak has demonstrated potential to be used in co-combustion with coal. In this research, we will study the cofiring of torrefied red oak with coal focusing on the kinetic study and reaction mechanisms. That is, the evaluation of the blending effect, terminal velocity of the particles, precombustion reactions, competition for oxygen, oxidizing and reducing reactions of carbon, hydrogen, and oxygen, combustion efficiency, thermochemical formation of ashes and gases, and pollutant emissions.

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THREE-YEAR RESULTS FROM THE FIRST FIELD TESTS OF AMERICAN CHESTNUT (*CASTANEA DENTATA*) BRED FOR BLIGHT RESISTANCE

Stacy L. Clark, Scott E. Schlarbaum, Arnold M. Saxton, and Fred Hebard[1]

An exotic fungus, the chestnut blight (*Cryphonectria parasitica* Murr. Barr), decimated the American chestnut tree (*Castanea dentata* Marsh. Borkh.) throughout eastern North America in the first half of the 20th century. The chestnut's demise had significant consequences on forest ecosystem processes and utilitarian values. The U.S. Department of Agriculture, Forest Service (FS), the University of Tennessee, and the American Chestnut Foundation (TACF) are collaborating on chestnut restoration research on National Forest System lands. In autumn 2007, TACF used their back-cross breeding program to produce chestnut trees that are predicted to be American chestnut in character with blight resistance from Chinese chestnut (*Castanea mollissima* Blume). Chestnut seedlings were grown as bare root 1-0 seedlings and then out-planted on three southern National Forests in 2009. We present 3-year results from these plantings that indicate chestnuts are capable of fast growth but may be susceptible to animal, insect, and disease pressure. Early indications are that the putatively blight-resistant generation, commonly referred to as the BC3F3 generation, resembles pure American seedlings in growth and phenology. We also report silvicultural considerations for field tests and reforestation efforts as well as partnerships that contributed to these activities.

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USING THE DENDROCHRONOLOGY PROGRAM LIBRARY (dplR) TO DOCUMENT THE INFLUENCE OF ENVIRONMENTAL CONDITIONS ON TREE GROWTH IN A KENTUCKY FOREST

Jared M. Craig, John M. Lhotka, and Jeffrey W. Stringer[1]

Dendrochronology is one of the most valuable methods of examining historical changes in forest growth and development. This study utilized manual dating techniques and statistical packages in conjunction with climatic data and forest records to assess the response of oak stands given various environmental conditions and disturbances. Three related sites located in the Knobs region of Kentucky were used for the study. All sites were oak-dominated stands typical of the area with a mean site index of 64 feet and average age of 110 years. Using the dendrochronology program library (dplR) for the R statistical language, cores were cross-dated, annual growth was standardized, and a master chronology was constructed. Historic weather data were then combined with forest records to create a timeline of site and regional-level events that occurred over the life of the stand. This timeline was then compared to the ring-width index value for each year within the master chronology to evaluate the response of stands to the historic environmental conditions and disturbances present in the study area.

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SYNTHESIS OF UNDERPLANTING OAKS TO SUSTAIN FUTURE OAK STOCKING

Daniel C. Dey, Emile S. Gardiner, Callie Schweitzer, John M. Kabrick, and Douglass F. Jacobs[1]

Oaks (*Quercus* spp.) are one of the most important tree taxa in the northern hemisphere with about 600 species. Although they are dominant in mixed-species forests and widely distributed, there are reports of regeneration failures worldwide and sustaining or increasing levels of oak stocking is problematic. Their ecological and economic value is almost unsurpassed by any other single genus, and forest succession to non-oak species is of great conservation concern.

The development of an adequate population of large oak advance reproduction is a critical prerequisite to successful oak regeneration, and hence sustainability of oak. The current state of many oak forests is that they lack oak advance reproduction, it is present but sparse, or it is abundant but small in size. Silvicultural practices that increase oak's regeneration potential permit oak seedlings to accumulate in the forest understory and to grow in size, and in particular root mass before the final regeneration harvest is done. Light in the understory is often cited as a limiting factor to accumulation and growth of oak advance reproduction, often occurring at levels at or below the light compensation point for oak. Light levels (20 to 50% +) sufficient for biomass production in oak reproduction results through management of the overstory, midstory, and understory density and composition. Stand thinning, shelterwood and group selection harvesting, and midstory removal have been used to promote development of oak advance reproduction. Artificial regeneration of oak by underplanting in thinned stands or in shelterwoods is done to supplement natural populations of oak seedlings or to introduce oak in stands where it is missing. Various stock types have been tested and the importance of stock quality is well-established. We review and synthesize the literature on silvicultural approaches to using artificial regeneration to obtain successful oak regeneration that is grounded in fundamental principles of oak biology and ecology.

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IMPACTS OF EMERALD ASH BORER ON FOREST VEGETATION STRUCTURE AND DIVERSITY IN HANCOCK COUNTY, OHIO

Benjamin Dolan[1]

Emerald ash borer (*Agrilus planipennis*) is an Asian beetle that was first discovered in Detroit, Michigan, in 2002. Emerald ash borer (EAB) was most likely transported in ash (*Fraxinus* spp.) wood that was used for stabilizing cargo in ships. The beetle has been spreading throughout the Central Hardwood Region since its introduction, and the ash population has been declining in response. EAB larvae feed on ash phloem and leave feeding grooves that impede nutrient and water transport, leading to mortality. EAB was identified in Hancock County, Ohio, in 2007, and the succession of vegetation that will occur after the disappearance of ash is unknown. It is hypothesized that vegetation diversity will decrease, sugar maple (*Acer saccharum*) will become dominant, and invasive plant species abundance will increase as a result of gaps created by ash tree mortality. Sites selected for this study include mature forests typical of northwest Ohio and are characterized by beech-maple and elm-ash forests. Vegetation sampling began in May 2010, prior to EAB-induced mortality, and will continue annually as ash succumbs to the invasive insect. Models predicting the potential change in vegetation indicate that sugar maple will become dominant immediately following ash death and will remain dominant over time in all but riparian and drier locations. Preliminary results indicate that green ash (*F. pennsylvanica*) is a generalist that binds divergent communities, which become more distinct upon removal of ash. Future composition of forest vegetation in northwest Ohio will be predicted with community succession models.

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DEMAND DRIVEN INDICATORS AND INNOVATIONS FOR THE GREEN BUILDING SECTOR

Greg Estep and David B. DeVallance [1]

Housing starts in the United States have decreased from approximately 2 million in 2005 to fewer than 600,000 in 2010. Products such as flooring, cabinetry, and mouldings produced from Appalachian hardwoods are heavily tied to new housing starts and consequently have suffered a similar decrease in demand. Opportunity exists in the Nation as the green building sector's market value is expected to increase by approximately 19.5 percent annually over the next 5 years. Much of the demand in the green building market is fueled from individual and corporate recognition of the environmental and energy savings associated with these standards of building. Green building standards require some form of forest certification, such as FSC, SFI or ATFS, to count the use of wood products towards meeting green building certification. However, supplying certified wood products to the green building market is not necessarily enough to ensure utilization of the material. For Appalachian hardwood producers to effectively penetrate green market sectors, it is important to fully understand the preferences and needs of the material specifiers of green building projects. Our study aims to determine the preferences and needs of green material specifiers within the Appalachian region through a direct mail survey. Survey results will relay material specifiers' views and ability to source green wood products within their region. Current and future demands for green wood products will be presented.

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ADVANCED OAK SEEDLING DEVELOPMENT AS INFLUENCED BY SHELTERWOOD TREATMENTS, FERN CONTROL, DEER FENCING, AND PRESCRIBED FIRE

Kurt W. Gottschalk, Gary W. Miller, and Patrick H. Brose[1]

Advanced northern red oak (*Quercus rubrum*) seedlings in an 80-year-old forest located in north-central Pennsylvania were observed for 8 years after manipulation of overstory density, herbicide control of interfering plants, exclusion of deer by fencing, and application of a single prescribed fire. Twenty-four treatment combinations including untreated controls were studied on 72 permanent plots. Published dominance probabilities for site index 70 were applied to the average size and number of tagged advanced seedlings in each plot to determine which treatments produced the greatest predicted number of codominant oaks in the next stand after final harvest. Exclusion of deer by fencing combined with a moderate (30% of basal area) to high (50% of basal area) removal of the overstory and herbicide control of hayscented fern (Dennstaedtia spp.) led to the most promising development of advanced oak seedlings in preparation for final overstory removal. Two of the 24 treatments met the SILVAH guidelines for overstory removal after 10 years, but just over half of the treatments would provide adequate oak regeneration using dominance probabilities to project success. Oak seedling development and suggestions for writing silvicultural prescriptions to prepare for successful oak regeneration are discussed.

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FIVE- AND SEVEN-YEAR DOMINANCE PROBABILITIES FOR OAK SEEDLINGS AND STUMP SPROUTS IN PENNSYLVANIA

Kurt W. Gottschalk, Gary W. Miller, and Patrick H. Brose[1]

The probability of survival and dominance of advanced oak regeneration stems and stump sprouts at 5 or 10 years postharvest is correlated with their preharvest size and vigor. A study was designed to: 1) determine the survival and dominance probabilities of oak advanced regeneration and stump sprouts for 5, 7, and 10 years after final removal cuts, and 2) determine if these probabilities vary significantly by ecological classification. Thirty-one timber sales in Pennsylvania state forests and Collins Pine property are included in the study, representing 6,235 tagged seedlings and 1,776 tagged stumps in four ecological sections. The 5-year data shows that 75 percent of the advance regeneration is still alive. Stump sprouts had higher losses with 66 percent mortality at 5 years. The surviving stumps had 5-year dominance probabilities of 0.38 and 7-year probabilities of 0.30 with smaller stumps having higher probabilities than larger stumps.

Classifying oak advanced regeneration as new seedlings (<0.25 in. root collar diameter [RCD]), established seedlings (RCD ≥0.25 in. and <0.75 in.), and competitive seedlings (RCD ≥0.75 in.), the larger the initial size of the seedling, the taller the 5-year old stem and the greater its dominance probability (new = 0.34, established = 0.57, competitive = 0.69). For 7-year-old seedlings, dominance probabilities were new=0.22, established=0.43, and competitive=0.62. Dominance probabilities reported here are greater than published values for other areas but will probably decline as crown closure occurs. A more conservative measure, free-to-grow produced much lower probabilities at age 5 years (new=0.04, established=0.13, competitive=0.27) and for age 7 years (new =0.1, established =0.16, competitive=0.3). Five-year and 7-year heights for the largest group of seedlings are on pace to match Schnur's site index curves for eastern oak forests (Schnur 1937).

Oak advanced regeneration dominance probabilities vary with initial seedling size with larger seedlings having higher probabilities. Five and 7 years postharvest is too early for final probabilities as crown closure has not been reached.

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CAN A PREHARVEST HERBICIDE TREATMENT FAVOR OAK REGENERATION IN A SHELTERWOOD HARVEST?

Todd F. Hutchinson, Joanne Rebbeck, and Daniel A. Yaussy[1]

In 2005, we began a study of tree regeneration in mixed-oak forests at three sites in southern Ohio. At each site, all non-oak+hickory competitors >2 inches diameter at breast height (d.b.h.) were stem-injected with herbicide (A.I. glyphosate 54%) in two of four 20-acre units, prior to shelterwood harvest. Five years after the harvest, we recorded the abundance of stump sprouts and advance reproduction by species in twelve 0.08-acre plots per unit (144 total plots). In nonherbicide units, stump sprouts of competing species (primarily red maple) were two times more abundant (97 sprouting stumps/acre) than that of oaks+hickories (44/acre). By contrast, stump sprouts of competitors (45/acre) and oaks+hickories (52/acre) were equally abundant in herbicide-treated units. For tall advance reproduction (stems >4.5 feet tall), competitors were about six times more abundant than oaks+hickories, regardless of herbicide treatment. The major competitors were red maple, yellow-poplar, blackgum, and sassafras. Smaller oak+hickory advance reproduction (1 to 4.5 feet tall) was moderately abundant on both nonherbicide (2,444 stems/acre) and herbicide-treated plots (1,735 stems/acre) but was typically overtopped. We concluded that, although herbicide treatments reduced the abundance of competing stump sprouts, oak+hickory advance reproduction was still being outcompeted and additional treatments such as prescribed fire are needed to retain oak dominance in the future stands.

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RESTORING BOTTOMLAND HARDWOODS: A SYNTHESIS OF TECHNIQUES AND METHODS

John M. Kabrick, Daniel C. Dey, J.W. Van Sambeek, Kyle L. Steele, Dawn E. Henderson, and Douglass F. Jacobs[1]

Restoring bottomland hardwoods in former agricultural fields has remained a challenge, and a number of Federal and statewide efforts to re-establish bottomland hardwoods have largely met with failure. High tree mortality due to herbivory, flooding, and intense competition by other native and invasive plant species has plagued management efforts. Here we summarize the findings from a number of studies conducted throughout the central United States to determine specific management methods and techniques for successful tree establishment. In these studies we examined the influence of native and invasive ground flora, cover crops, slow-release nitrogen fertilizers, animal browse, soil bedding, planting stock type, flooding, and species suitability on the survival and growth of hardwood seedlings. Most flora recolonizing abandoned crop fields were invasive agricultural species including Johnsongrass (*Sorghum halepense* [L.] Pers.), reed canarygrass (*Phalaris arundinacea* L.), hedge false bindweed (*Calystegia sepium* [L.] R. Br.), lambsquarter (*Chenopodium album* L.), and pigweed (*Amaranthus* L.). Redtop grass (*Agrostis gigantea* Roth) as a cover crop reduced recolonization of both native and invasive species but had the added benefit of reducing herbivory. Application of slow-release nitrogen fertilizers on the alkaline soils failed to improve sapling growth. Restoring microtopography through soil bedding improved drainage and other soil properties but only increased the growth of seedlings in clayey, poorly-drained soils. Containerized planting stock consistently had higher survival than bare-root stock under a variety of hydrologic conditions. Surprisingly, most bottomland oaks are fairly tolerant to short-duration growing season floods. Collectively, these findings provide a variety of techniques and methods than can be tailored to the site conditions to optimize the establishment of bottomland hardwood seedlings.

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QUANTIFYING SEEDLING FLOOD TOLERANCE IN AN OUTDOOR FLOOD TOLERANCE LABORATORY

John M. Kabrick, Daniel C. Dey, J.W. Van Sambeek, Mark V. Coggeshall, and Douglass F. Jacobs[1]

Ensuring successful hardwood tree establishment requires matching the ecological requirements and tolerances of the species to the environmental conditions of the planting site. In bottomlands, it is particularly important that the planted seedlings are tolerant of the present-day flood regime. Although much is known about the factors that influence flood tolerance, flood tolerance ratings remain largely qualitative. Here we report on an effort to more quantitatively examine flood tolerance by measuring the survival and growth after flooding of six bottomland species common throughout much of eastern North America in a state-of-the-science outdoor flood tolerance laboratory that allows for the control of the timing, duration, and nature of flooding. We evaluated 600 plants each of six species including eastern cottonwood (*Populus deltoides*), pin oak (*Quercus palustris*), swamp white oak (*Q. bicolor*), bur oak (*Q. macrocarpa*), black walnut (*Juglans nigra*), and pecan (*Carya illinoensis*). All stock was from the Missouri State Nursery and included cuttings for cottonwood and 1-0 bareroot stock for all other species. Flood treatments included partial inundation to 15 to 20 cm for 5-week flowing, 5-week stagnant, 3-week flowing, and control and were replicated in space and time. For each experiment, plants were established in April, flood treatments were initiated in May, and seedling survival and growth (including shoot length, the number of flushes, and the cumulative flush length) were evaluated at the end of the growing season in September. Survival data were analyzed using logistic regression and growth was analyzed using linear models. Cottonwood maintained moderate survival probability (0.62) and high growth but had a significant basal diameter growth reduction with increased flood duration. Bur oak, swamp white oak, and pin oak each had greater survival probabilities than cottonwood, exceeding 0.77 regardless of treatment. Swamp white oak maintained positive growth and maintained healthy dark green foliage in all treatments and bur oak and pin oak suffered shoot growth losses and exhibited chlorotic foliage in flood treatments. Pecan maintained high survival (0.78) but suffered dieback. Black walnut had the lowest survival (0.11) and growth with increasing flood duration. Our findings show both consistencies and discrepancies with published flood tolerance ratings for these species. There generally is good agreement in the literature that black walnut is intolerant and eastern cottonwood is tolerant to very tolerant of flooding, as our findings confirm. Higher cottonwood survival probabilities may have been achieved with planted seedlings rather than with cuttings. However, the published flood tolerances of the bottomland oaks that we examined ranged from intolerant to tolerant and no single species consistently was rated in the literature as more tolerant than the others. Our findings strongly suggested that swamp white oak is more tolerant to flooding than are the other oaks we examined and appears to tolerate flood treatments better than did eastern cottonwood cuttings, suggesting its suitability for planting in a variety of bottomlands.

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COMPARISON OF TWO STEM INJECTION TREATMENTS APPLIED TO AMERICAN BEECH IN CENTRAL WEST VIRGINIA

Jeffrey D. Kochenderfer, Gary W. Miller, and James N. Kochenderfer[1]

Efficacies for two herbicide stem injection treatments on American beech (*Fagus gandifolia* Ehrh.) and impacts to nontarget residual trees were evaluated in central West Virginia. The treatments consisted of hack-and-squirt injection of all beech stems >1.0 in. to 9.9 in. diameter at breast height (d.b.h.) with either imazapyr as Arsenal® (28.7%) or glyphosate as Razor® Pro (41%) in water carriers. The treatments were applied in September 2008 and evaluated 12 months after treatment. Complete control of injected stems was achieved with both treatments, however, treatment efficacy on untreated beech stems >1.0-ft tall and >0.9 in. d.b.h. was higher on the Arsenal® treatments. No damage occurred to any desirable overstory species such as black cherry (*Prunus serotina* Ehrh.) or red maple (*Acer rubrum* L.) trees that were located on all the treatment plots. Land managers can use the hack-and-squirt injection treatments described in this study to control injected trees and a large proportion of smaller beech root sprouts associated with them.

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INVASION AND SPREAD OF INVASIVE PLANTS IS A MAJOR PROBLEM WITHIN FORESTED ECOSYSTEMS

Chris B. LeDoux, Danielle K. Martin, and Cynthia D. Huebner[1]

Invasive plants can displace existing vegetation and in some cases take over the site entirely. With the displacement of native vegetation comes ecosystem changes that may jeopardize ecological processes and functions and habitat for wildlife. The disturbance caused during timber harvesting processes creates conditions whereby invasive plants may get established and/or spread. The machinery and traffic movement within a job site may serve to introduce and spread seeds, roots, and plant parts from one job site to another. In an upcoming general technical report (LeDoux and Martin, in press) to be published by the U.S. Forest Service, Northern Research Station, we address the timber harvesting processes and the disturbance that is created, how seeds, roots, and plant parts of invasive plants can be spread, and propose voluntary BMPs for invasive plant mitigation during timber harvesting operations.

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RESPONSES OF NORTHERN RED OAK SEEDLINGS TO LIME AND DEER EXCLOSURE FENCING IN PENNSYLVANIA

Robert P. Long, Patrick H. Brose, and Stephen B. Horsley[1]

In Pennsylvania, two hypotheses compete for explaining the chronic oak (*Quercus* spp.) regeneration problem: excessive deer browsing and soil cation depletion. We tested these hypotheses by evaluating the effect of forest liming and deer exclosure fencing on northern red oak (*Q. rubra*) seedling growth and nutrition in five oak shelterwood stands in Pennsylvania over 6 years. In each stand, four planting plots were located inside of a 2.4 m high woven wire fence and another four were established outside of the fence. About 225 northern red oak acorns were planted in each plot in spring 2004. Dolomitic limestone was applied to randomly selected plots at rates of 0, 4.5, 9.0, and 13.5 Mg ha^{-1} during May 2004. There were no statistically significant ($P \leq 0.05$) growth responses to lime applications. The only significant growth responses resulted from the fence versus no fence treatment. A significant ($P < 0.003$) fence-by-year interaction for seedling height and root collar diameter indicates differential impacts of deer browsing. By 2009, height of seedlings inside fences averaged 32 cm while seedlings outside of fences averaged 17 cm. Similarly, root collar diameter averaged 6.6 mm outside of fences and 9.1 mm inside fences. Fencing had a significant effect on seedling biomass components evaluated at the conclusion of the study, with seedlings inside fences having greater root length and total dry weight biomass than seedlings grown outside of fences. Application of up to 13.5 Mg ha^{-1} lime will not accelerate northern red oak seedling growth.

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TWO DECADES OF CHANGE IN THE COMPOSITION AND STRUCTURE OF OLD-GROWTH FORESTS IN THE CENTRAL HARDWOOD REGION

Christy Lowney, Michael Jenkins, Martin Spetich, Stephen Shifley, and Bradley Graham[1]

The Central Hardwood Region has historically been dominated by oak forests, woodlands, and savannas. Through the clearing of land for agriculture and infrastructure, the amount of forested land in Indiana has been reduced, leaving small patches of remnant oak and oak/hickory old-growth forests often less than 30 ha in size. Fragmentation coupled with the removal of fire from the landscape is resulting in a compositional shift in these forests. Forests previously dominated by oak (*Quercus*) and hickory (*Carya*) species are shifting to dominance by maple (*Acer saccharum* and *A. rubrum*) and American beech (*Fagus grandifolia*). To gain a better understanding of long-term changes in old-growth forests of the Central Hardwood Region, permanent plots were established in five remnant old-growth forests throughout Indiana in 1992-93 and remeasured in 2011. Thirty plots were sampled in each forest. At each site, data were collected to assess changes in ground cover, seedlings, saplings, shrubs, and trees. Data from these five forests will be used to examine overstory mortality, with a focus on the dominant oak cohort, and compare changes in the density and basal area between 1992-93 and 2011. At most of the sites, preliminary results show an increase in overstory sugar maple (stems ≥10 cm diameter at breast height), suggesting that these stands will be dominated by shade-tolerant species in the future.

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COMPOSITION AND STRUCTURE OF EASTERN HEMLOCK FOREST ECOSYSTEMS OF NORTHEASTERN OHIO PRIOR TO HEMLOCK WOOLLY ADELGID INFESTATION

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Ohio's eastern hemlock (*Tsuga canadensis* L.) forest ecosystems provide important ecological and economic benefits to the State. Since its introduction in the 1950s, hemlock woolly adelgid (*Adelges tsugae* Annand; HWA), an invasive insect native to Japan, has been causing widespread mortality of eastern hemlock in an expanding portion of its range. In January 2012, the first known HWA infestation in Ohio was discovered in the southeastern portion of the state. Before this introduced pest reaches eastern hemlock swamp forests of the Erie Lake Plain and stream-ravine forests of the glaciated Allegheny Plateau in northeastern Ohio, understanding their current composition and structure is critical for predicting potential pathways of stand development in response to the possible decline of eastern hemlock. Vegetation (trees, saplings, and ground flora), down woody debris, and canopy closure (via hemispherical photography) data were measured on 0.2-hectare plots at seven sites throughout northeastern Ohio. Samples of the soil seed bank were also collected to determine plant species present in the forest floor. Preliminary analyses show that the importance value of eastern hemlock at these sites ranges from 33 to 95 percent. On 94 percent of the plots, eastern hemlock was the only coniferous tree species present, meaning the potential loss of this foundation species would drastically affect species composition and functional processes. Future development patterns are being examined using the Forest Vegetation Simulator in conjunction with the Hemlock Woolly Adelgid Event Monitor to simulate HWA-induced mortality and predict stand growth and development.

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TO WHAT EXTENT ARE WOODLAND NEIGHBORS TALKING? AN ASSESSMENT OF INTERACTIONS BETWEEN ADJACENT WOODLAND OWNERS

Megan McCuen and David W. McGill[1]

Most of West Virginia's forested land is owned by private landowners. When combined, individually owned woodlands significantly impact the whole landscape. Working across property boundaries is one way to promote enhanced environmental quality and to make woodland activities more financially rewarding. As natural resources management agencies focus on landscape-scale conservation, cross-boundary cooperation becomes increasingly important. We developed a survey to assess the extent, frequency, content, and quality of communication and cooperation among adjacent woodland owners. The purpose of the survey is to gain knowledge about West Virginia woodland owners, what they do in their woodlands, and their experiences working with their neighbors. Results will be published in McCuen et al. (in press).

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ASSESSING PAST EPICORMIC DYNAMICS IN POLE-SIZE WHITE OAK LOGS WITH CT SCANNING

Andrew Meier, Rado Gazo, Charles H. Michler, and Michael R. Saunders[1]

White oak (*Quercus alba* L.) is one of the most valuable and ubiquitous species in the Central Hardwoods Forest Region (Rogers 1990). It is also well-known for its tendency to form epicormic sprouts (Johnson et al. 1998), potentially leading to decreased log value. Epicormic branching is a phenomenon that is still poorly understood (Meadows 1995), though there is strong evidence that both genetics (Bowersox and Ward 1968) and tree vigor (Johnson et al. 1998) are important factors that influence sprouting in individual trees. Many studies have assessed external epicormic characteristics, however, there is increasing evidence that prior epicormic development may be an important determinant of current epicormic status (Colin et al. 2010, Morisset et al. 2012). The objective of this study was to quantify the number and development of epicormic bud traces evident in white oak logs in terms of genetics and tree vigor, using computed tomography (CT) scanning as a tool to rapidly assess a large sample of logs (Colin et al. 2010, Morisset et al. 2012). We also hoped to determine whether there was a correlation between regular branch formation and formation of epicormics. White oak logs for this study were removed as part of a crop tree release treatment in two 28-year-old white oak progeny tests in Indiana, at the Jasper-Pulaski Fish and Wildlife Area (JP) and the Harrison-Crawford State Forest (HC). In 2006, all trees in the plantations were ranked qualitatively for epicormic branching; family averages for these rankings were calculated and families with the highest, lowest and median values were assigned to corresponding epicormic classes (EpiC). A subset of families from these classes was selected for study. Within selected families, individuals were identified based on canopy classes (Can), with the objective of selecting trees of high and low vigor from each family for analysis. External counts of epicormic branches were made on the bottom 12-foot section of each selected tree in January and February of 2010; trees were then felled and the second 4-foot section was removed for CT scanning. Logs were scanned using a GE Lightspeed QX/i multislice helical CT scanner (General Electric, Fairfield, CT) at the Purdue University College of Veterinary Medicine. Resulting images were analyzed manually using open access ImageJ software with the cell-counter plug-in. Epicormic structures were characterized by their size and development. They were also classified as primary or secondary, with primary traces originating at the pith of the main stem and secondary traces originating at the pith of another branch. Distinctions were based largely on the descriptions of epicormic structures from Fontaine et al. (1999) and Colin et al. (2010). In general, the number of epicormic traces per tree was quite variable and not significantly different between sites, about 55 (sd = 24.4) at JP and 47 at HC (sd = 27.3). The number of regular branches per tree was identical at both sites (21.3; JP sd = 3.8, HC sd = 4.6) and did not differ between EpiC or Can. It is therefore improbable that the number of regular branches can explain tree-to-tree variation in epicormics. No significant differences were detected between either Can or EpiC in either the total number of epicormic traces or PS. For EpiC, both the percent of unsprouted traces (Pr > chi-square = 0.04) and the number of large epicormic traces (maximum diameter >2.5 inches) (Pr > chi-square = 0.01) were significantly different between classes, suggesting that there may be some genetic difference in epicormic sprouting and branch persistence. Further analyses will relate growth parameters, such as radial increment, tree diameter, and crown volume with the internal development of epicormic structures.

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SURFACE ENERGY ANALYSIS ON HOT-WATER EXTRACTED AND TORREFIED APPALACHIAN WOOD SPECIES FOR PELLET PRODUCTION

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Our research evaluated the surface area and surface energy properties of pretreated underutilized renewable biomass composed of red oak (*Quercus rubra*) and yellow-poplar (*Liriodendron tulipifera*.) regarding their feasibility to be densified. The pretreatments consisted of hot water extraction and torrefaction processes. The extraction process was performed at different temperatures and times and the final measurements included extraction yield (weight loss), sugars, and lignin determination. Torrefaction process was performed using two particle sizes of material at two different temperatures and times. Characterization of the torrefied material included calorific value and proximate and ultimate analysis. Nonextracted, extracted, and torrefied material were pelletized at a fixed temperature and time, and mechanical evaluation through flexure measurements on pellets was performed. The surface properties of the pretreated material to evaluate their feasibility for pellet production were evaluated using inverse gas chromatography. Surface area was determined using nonane as a probe and surface energy, i.e., dispersion and acid-base component, was determined through the exposition of all different materials to low vapor concentrations of nonpolar (decane, nonane, octane, heptane) and polar (ethyl acetate, dichloromethane, acetone, 1-propanol) probes. Results indicate that the surface area and surface energy is playing an important role in the final properties of the material which are directly related to the processing and mechanical properties of the wood pellet.

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PREDICTING THE IMPORTANCE OF PRESCRIBED FIRE AND MANAGEMENT ACTIVITIES ON THE PRESENCE AND ABUNDANCE OF *AILANTHUS ALTISSIMA* WITHIN FORESTED LANDSCAPES

Joanne Rebbeck[1]

Ailanthus altissima, a highly invasive tree, is present in many forested landscapes in the eastern United States. Although managers often observe an expansion in *Ailanthus* populations following forest disturbances such as harvesting and prescribed burning, there is little empirical data available to confirm. Seed-bearing female *Ailanthus* were aerially mapped (N=98) during the 2008-2009 dormant season within 3,885 ha of Tar Hollow State Forest located in southern Ohio. During the 2009 growing season, a systematic georeferenced 400-m grid of 280 plots was sampled to quantify *Ailanthus* abundance and demography and stand attributes. Harvest and fire disturbance indices were developed by summarizing past timber harvest records over ~65 years and evaluating vegetation impacts of dormant season prescribed burns from 2000 to 2008. A geographic information system (GIS) database of these disturbance indices plus potential seed dispersal patterns, overstory composition and density, distances to seed sources and roads (e.g., skid, logging, hiking, primary, secondary, etc.), and soil moisture was developed. Multiple statistical analyses were performed on distance-time dimensions to determine the extent to which harvesting and/or burning favors the spread of the *Ailanthus*. Classification and regression trees (CART) and Random Forests were used to uncover relationships among these diverse sets of variables. Preliminary analyses found that seed-bearing trees within the forested landscape were more common in areas that had any type of past harvesting activity (81.6%) compared with those in uncut areas (18.4%).

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EFFECTS OF SHELTERWOOD HARVESTS, PRESCRIBED BURNING, AND DIAMETER-LIMIT CUTTING ON NORTHERN RED OAK (*QUERCUS RUBRA*) UNDERPLANTINGS

Adam Regula, David W. McGill, and Cynthia D. Huebner[1]

Despite the dominance of oak in much of the Central Hardwood Region, there has been a significant and documented decline in regeneration over the past 40 years. As many oak species are of significant ecological, economic, and cultural value, this decline has been the subject of substantial research. Ultimately, management for oak entails the establishment of advanced reproduction of sufficient size and density to provide a high probability of ascendancy to dominant and codominant status. Potential prescriptions for achieving this include manipulating light infiltration and controlling competing vegetation through shelterwood harvests and prescribed burning. Diameter-limit cutting is a primary harvest method used on private forests in the region and creates diverse postharvest conditions which can favor fast growing, shade intolerant competition or shade tolerant species depending on the initial structure of the harvested stand and the minimum diameter harvested. Our study examines the effect of five management regimes on northern red oak (*Quercus rubra*) artificial reproduction through a 2-year assessment of the survival and growth of 1-0 planted bare root seedlings. Treatments consist of: 1) control sites with no disturbance for at least 50 years; 2) a single prescribed burn; 3) repeat prescribed burns; 4) shelterwood harvests (average 40% residual basal area); and 5) diameter-limit cuts removing merchantable trees >16 inches diameter at breast height. Each treatment is replicated on four sites, two within the Allegheny Plateau province and two within the Ridge and Valley province. Transects are established in such a way that each site has two blocks, a northeast and southwest aspect. This allows for comparison across these existing environmental gradients. Seedlings were planted during April and May 2011. Survival was 70 percent overall, with higher survival in the Ridge and Valley (73%) than Allegheny Plateau (64%). Among management regimes, survival was highest under shelterwood harvests (86%) and lowest on control sites (54%). No strong pattern appeared among management regimes regarding height growth. Average height growth was 15 cm in the Allegheny Plateau and 11.8 cm in the Ridge and Valley.

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SEEDBANK COMPOSITION ON FORMER HOME SITES IN A HIGHLY DISTURBED OAK-HICKORY-PINE FOREST

Jamie L. Schuler[1]

The primary mandate of the Hot Springs National Park (HOSP) is the protection and preservation of the geothermal springs and their recharge zones. Since the 1970s, HOSP has acquired and removed structures from more than 300 old home sites within the semi-forested geothermal recharge zone. These former home sites were then allowed to naturally revegetate with the goal of establishing new areas of native upland oak-hickory-pine forests. However, several species of invasive, nonnative plants have aggressively colonized these disturbed lands, are out-competing native vegetation, and are threatening the overall health, structure, and functions of the upland forest ecosystem. Initial management activities have focused on the targeted removal of the invasive species, often without consideration of the subsequent recruitment potential of native species. To assess the likelihood that native species will regenerate if the existing nonnative species are removed, the soil seedbank was sampled in stands representing three time periods: <10 yr, 10 to 20 yr, and 60+ yr after disturbance. Results indicate that stands on the recently (<10 yr) disturbed home sites had moderate numbers of nonnative woody germinants, while stands that were disturbed 10 to 20 yr ago had high numbers of nonnative germinants. By contrast, the seedbank sampled from native forests that were undisturbed for more than 60 yr contained almost no nonnative species. The results highlight the significant problems associated with managing established, nonnative species in recently disturbed landscapes.

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USING ECOLOGICAL SITES TO GUIDE SPECIES SELECTION IN BOTTOMLAND HARDWOOD PLANTINGS

Kyle L. Steele, Jason L. Villwock, John M. Kabrick, and Randy G. Jensen[1]

In bottomland afforestation efforts, site conditions related to flood duration, soil drainage, and nutrient supply greatly affect tree seedling survival and growth. Ecological classification systems group land units by site conditions resulting from different soil properties on varying landform positions into ecological sites that greatly influence tree seedling establishment success. Here we report the first-year survival and growth of 12 bottomland species planted on five different ecological sites. Results to date show that both seedling survival and growth (diameter and height) were not different across ecological sites. Most species responded similarly to ecological site, with the exception of cottonwood (*Populus deltoides*), sycamore (*Platanus occidentalis*), and river birch (*Betula nigra*). All 12 species planted had survival between 88 and 95 percent with the exception of cottonwood which had 41 percent. However, surviving cottonwood had significantly greater ($P<0.01$) height and diameter growth compared to all species. After cottonwood, both sycamore and river birch had significantly ($P<0.01$) greater height and diameter growth. For species by treatment effects, sycamore had significantly greater ($P<0.01$) diameter growth on mesic high-elevation floodplains while cottonwood had significantly greater ($P<0.01$) diameter growth on mesic terrace landforms (both contain silty-textured soils). These findings complement several research projects in Missouri that have studied specific management techniques to improve the success of old field bottomland reforestation including evaluating seedling stock type, use of cover-crops, use of various herbicides, tree species, seedling flood tolerance, soil mounding, and seedling caging. This information is useful to field managers who are interested in making bottomland reforestation efforts most successful by selecting the appropriate species for sites with varying soil moisture, texture and flooding frequencies. Early results appear to show that ecological sites having silty-textured soil occurring on high floodplains and terraces provide optimal growing conditions for survival and growth of planted seedlings. Other ecological sites may require additional management input.

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BEST MANAGEMENT OPPORTUNITY MODEL USED FOR RESTORING CHESTNUT TO THE LANDSCAPE

Scott Tepke, Veronica A. Lopez, and Jeanne M. Hickey[1]

American chestnut (*Castenea dentata*), once common to forests of the eastern United States, has been nearly extirpated by a fungal disease called the chestnut blight (*Cryphonectria parasitica*). Efforts by the American Chestnut Foundation have led to sixth generation hybrid chestnut trees with an increase in resistance to the blight. To increase the opportunity for chestnut to grow and reproduce on the landscape, selecting optimal sites to grow chestnut is imperative. A model was developed to aid in selecting sites. A literature review indicated that American chestnut performance is tied to soil type characteristics. To create a model that would select optimal site characteristics, data layers were ranked. Soil types were ranked by soil drainage characteristics, and forest types were ranked by association with American chestnut. A 200-foot buffer was applied to drainages to avoid soil inclusions and water quality issues. Aspect and slope data were used to refine the model within each optimal site. The study area, the Millsteck Project in the southern part of the Allegheny National Forest, was used to test and verify the model. Allegheny National Forest geographic information system (GIS) specialists analyzed the data and created a map of optimal sites within watersheds, and then overlaid the Millsteck silviculture treatment areas. Treatment areas proposed for regeneration treatments that overlaid best management sites were selected for field evaluation. Sites were visited to evaluate the feasibility of establishing chestnut restoration sites and seed production plantings. By modeling the best opportunity areas, land managers will be able to improve the success rates of chestnut restoration efforts.

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WHEN ONE IS NOT A LONELY NUMBER: INITIAL COLONIZATION DYNAMICS OF HEMLOCK WOOLLY ADELGID (*ADELGES TSUGAE*)

Patrick C. Tobin, Richard M. Turcotte, and Daniel Snider[1]

A central and ongoing question in invasion ecology is why establishment success in a new environment varies so markedly among and within species. In many low-density populations of invading insects, establishment success can be challenged by stochasticity and Allee effects, which can arise due to the inability to find suitable mates, saturate natural enemies, and overcome host plant defenses in sparse populations. The hemlock woolly adelgid, *Adelges tsugae*, is a nonnative species that attacks and kills eastern North American species of hemlock. However, there is little information regarding its invasion success at low densities. Because *A. tsugae* reproduces asexually and natural enemies are rare or absent in expanding populations, many of the documented causes of an Allee effect in insect populations are not relevant to its invasion dynamics. We inoculated hemlock trees with varying densities of *A. tsugae* over 2 years and observed a positive relationship between density and colonization success. In some cases with an initial density of one ovisac per tree, we observed successful establishment, development, and the initiation of a subsequent generation. Understanding the drivers of initial establishment success could be useful in developing more effective management strategies against this nonnative pest.

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NATURAL REGENERATION IN WEST VIRGINIA: SURVEY OF ISSUES FACING NATURAL RESOURCES PROFESSIONALS

Ellen Voss and David W. McGill[1]

Most forest regeneration in West Virginia is natural hardwood regeneration. A lack of information about problems with forest regeneration has been identified as a significant data gap by the West Virginia Division of Forestry. A great deal of anecdotal information has come from field foresters and other natural resource professionals who are observing changes in the quality of regeneration.

Invasive species, excessive deer herbivory, timber harvest practices, and wildfire are among the concerns that are frequently expressed at professional trainings and informal walks in the woods.

Our research project involves a mailed survey to about 600 natural resource professionals to determine their level of satisfaction with the quality of forest regeneration in West Virginia. The survey will begin the process of documenting the types of concerns related to regeneration and examining the geographic locations and spatial variability of regeneration issues. Surveys were mailed to members of the West Virginia Division of Society of American Foresters, certified foresters and forestry technicians registered with the West Virginia Board of Registered Foresters, wildlife biologists employed by the State, and various other ecologists and natural resource professionals employed by the U.S Forest Service, U.S. Fish and Wildlife Service, and nonprofit organizations. Results are published in Voss 2012.

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INTERSPECIFIC VARIATION IN TREE SEEDLING HEIGHT GROWTH RESPONSES TO HARVEST GAP SIZE: IMPLICATIONS FOR INCREASING TREE DIVERSITY IN MESIC NORTHERN TEMPERATE FORESTS

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Tree species diversity in northern hardwood forests may be declining due to white-tailed deer (*Odocoileus virginianus*) herbivory, catastrophic forest health epidemics, harvest legacies, and other factors. Bottlenecks may be particularly strong for trees < 1.5 m tall as this corresponds to the maximum height of both competing nontree vegetation and browsing deer's reach. Thus, encouraging fast growing species in environments that foster that potential (high light and soil resources) may be effective means of increasing tree diversity. Alternatively, greater resources could promote greater growth of competing nontree vegetation. For weeded plots with 14 species of planted tree seedlings and adjacent unweeded, unplanted plots distributed over a range of harvest gap sizes, we predicted: 1) seedling growth and competing nontree vegetation density will increase in response to canopy gap size/light and soil resources (water and nitrogen); 2) tree seedling responses will be unique and related to shade tolerance classifications; and 3) variation in tree species and competing vegetation responses to resources can be used to help inform restoration practices. Light ranged from 2.5 percent of open sky light in undisturbed understory to > 30 percent in multitree gaps exceeding 900 m^2. Competing nontree vegetation responded to harvest gap light such that light levels beneath competing vegetation across all gap sizes could be as low as in undisturbed understory plots. However, levels were variable due to the positive impacts of water on competing vegetation and variation in water availability among gaps. Height growth varied greatly among species, with shade intolerant species and midtolerant American elm (*Ulmus americana*) and yellow birch (*Betula alleghaniensis*) generally growing faster than tolerant species. Shade intolerant species also generally responded to soil nitrate availability, tolerant species to ammonium, and no tree species responded to water. In conclusion, in larger, greater light gaps with high soil nitrogen availability, many species, especially those less tolerant, can attain heights beyond which they escape the potential for deer browse and interference from competing nontree vegetation. Tree seedling growth is unresponsive to water, whereas competing vegetation density increases with water; suggesting that tree seedlings may more likely escape nontree competition in drier gaps. Supporting this notion, the density of naturally established pine and cherry seedlings emergent from the competing vegetation canopy was greater in drier gaps. Thus, tree diversity restoration efforts could be aimed at creating larger gaps on drier sites with potentially less competing vegetation and perhaps planting species with rapid height growth where necessary.

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EFFECTS OF SCARIFICATION AND HARVEST GAP SIZE ON TREE SEEDLING ESTABLISHMENT

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Increasing species diversity is becoming an important silvicultural objective. In the managed northern hardwood forest of the Great Lakes region, species diversity may be constrained, in part, by reductions in bare mineral soil and decaying coarse woody debris seedling establishment substrates and by low understory light levels in selection-managed stands. Small-seeded species, including yellow birch (*Betula alleghaniensis*), paper birch (*B. papyrifera*), and eastern hemlock (*Tsuga canadensis*), may be particularly sensitive to some of these factors, as, in carbon-limited understories, they lack the carbohydrate reserves necessary to facilitate root growth and establishment in a broad range of substrates. To identify which factors are currently governing seedling establishment, we are conducting an experiment in Emmet County, Michigan, to quantify the effect of increasing bare mineral soil and coarse woody debris substrates (i.e., favorable substrate) on seedling establishment across a gradient of harvest gap sizes. In May 2011, plots were established in each of 40 harvest gaps and four unharvested locations. Subplots were assigned the treatments: 1) scarification (raking away the organic layer to increase favorable substrate availability) and competing nontree vegetation clipping; 2) scarification only; 3) competing nontree vegetation clipping only; and 4) no treatment. Five hundred seeds of yellow birch, paper birch and eastern hemlock were added to each subplot to augment the natural seed-rain. In August 2011, the first of multiyear measurements of forest floor substrate coverage, competing vegetation and tree seedling numbers were conducted. Preliminary results indicate that seedling establishment of small-seeded species paper birch, hemlock, and pin cherry (*Prunus pensylvanica*) (with its persistent soil seed bank) can be increased with increasing forest floor disturbance and exposure of favorable mineral soil and coarse wood substrates. Seedling establishment increased fourfold for paper birch (2,387 seedlings/ha), elevenfold for hemlock (6,733 seedlings/ha), and twofold for pin cherry (2,955 seedlings/ha) in scarified plots. However, the response of individual species varied across the harvest gap-size gradient. Hemlock was more responsive to scarification in 100-400 m^2 harvesting gaps, while paper birch and pin cherry were more responsive in 500-1200 m^2 harvesting gaps. Seedlings of all species were scarce in harvesting gaps greater than 1200 m^2 independent of scarification. Although preliminary, these results suggest that scarifying the forest floor beneath a range of canopy gap sizes up to 1200 m^2 can initially promote the establishment of a small-seeded species cohort. Continued monitoring, including the consideration of the effects of scarification on competing vegetation, will generate stronger conclusions regarding the efficacy of scarification and weeding on seedling establishment in northern hardwood forests.

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URBANCROWNS: A SOFTWARE TOOL FOR ASSESSING AND MONITORING URBAN TREE CROWNS

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Trees play an important role in urban communities. In addition to the aesthetic benefits they provide, urban trees also filter harmful pollutants from the air and water, lower emissions of volatile organic compounds (VOC), and reduce heating and cooling energy consumption. Two important characteristics used to quantify urban tree benefits are crown size and tree health, both of which can be difficult to ascertain. For this reason, the U.S. Forest Service Southern Research Station has developed a software tool to assist urban foresters, arborists, and community volunteers with assessing and monitoring urban tree crowns. The program analyzes a single, side-view digital photograph of a tree and computes the following crown metrics: height, diameter, ratio, volume, density, and transparency. UrbanCrowns can be used to monitor tree crowns over time to provide early detection of disease, insect, or storm damage. It can also be used to quantify tree benefits related to crown size and density such as rainfall interception and pollution removal.

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GROWTH RESPONSE OF INTENSIVELY MANAGED BLACK WALNUT (*JUGLANS NIGRA* L.) TO VARYING INTENSITY PRUNING REGIMES: EARLY RESULTS

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The high value of black walnut (*Juglans nigra* L.) as a timber tree makes it especially suited to highly intensive plantation management. In such systems, crown expansion occurs rapidly, necessitating the inclusion of green pruning into cultural practices to facilitate good stem form and the production of high quality wood. While more intensive pruning practices may yield improvements in stem form and wood quality, the resulting removal of leaf area could decrease growth rates, thus increasing rotation periods. In this study, we examine the 2-year growth response of an 11-year-old plantation of black walnut as affected by pruning intensity and timing. Pruning intensity treatments included the following: high intensity, in which all branches below 4.0 m high, as well as codominant branches (branches >3 cm with strong branch angles) within the crown were removed; low intensity, where all branches below 2.5 m high were removed; and control. Pruning treatments were applied during either dormancy (late November to early March), leaf expansion (mid to late June), or at maximum leaf area (late July to early August). Leaf area, for both pruned and retained branches, was estimated using allometric models developed in a parallel study. Impacts on growth (height and diameter) were then examined as a function of leaf area reduction. Early results suggested no difference in absolute diameter growth by treatment ($p = 0.772$) or height growth ($p = 0.533$). Therefore, young black walnut may tolerate removals of 40 percent of leaf area without significant loss of growth.

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