Scandinavian Journal of Forest Research
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713711862

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Online publication date: 14 July 2010

To cite this Article Berrill, John-Pascal and Dagley, Christa M.(2010) 'Assessing longleaf pine (*Pinus palustris*) restoration after southern pine beetle kill using a compact experimental design', Scandinavian Journal of Forest Research, 25: 1, 75 — 85
To link to this Article: DOI: 10.1080/02827581.2010.485821
URL: http://dx.doi.org/10.1080/02827581.2010.485821

Scandinavian Journal of Forest Research, 2010; 25(Suppl 8): 75–85

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ORIGINAL ARTICLE

Assessing longleaf pine (*Pinus palustris*) restoration after southern pine beetle kill using a compact experimental design

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Abstract

A compact experimental design and analysis is presented of longleaf pine (*Pinus palustris*) survival and growth in a restoration project in the Piedmont region of Georgia, USA. Longleaf pine seedlings were planted after salvage logging and broadcast burning in areas of catastrophic southern pine beetle (*Dendroctonus frontalis*) attacks on even-aged mixed pine–hardwood forests. The split-plot design with randomized complete blocks was replicated on four sites. Main treatments were: chemical control of competing vegetation with herbicides; mechanical mowing to remove above-ground competition; and an untreated control. Nested within fixed-area treatment plots were single-tree plots centered on longleaf pine seedlings where adjacent vegetation was assessed immediately before treatment in years 1 and 2. Treatments applied to single-tree plots comprised three sizes of sprayed area around seedlings in chemical treatment plots. Logistic mixed-effects models indicated that initial survival was impacted by herbaceous vegetation but remained unaffected by the various vegetation control treatments applied later in year 1. Control of above- and below-ground competition around planted seedlings by mowing in conjunction with herbicide treatments resulted in significantly greater frequency of emergence from the grass stage, accelerating development of longleaf pine planted to restore beetle-killed areas in the Piedmont region of Georgia.

Keywords: *logistic mixed-effects model,* Pinus palustris*, split-plot design, stand establishment, weed control.*

Introduction

Catastrophic outbreaks of the southern pine beetle (*Dendroctonus frontalis* Zimmerman) are being recorded throughout the south-eastern USA. On the Hitchiti Experimental Forest in central Georgia, approximately 200 ha ($\sim$10% of the forested area) was lost in 2007 (J. Moore, personal communication). Aging stands of loblolly pine (*Pinus taeda* L.) are especially vulnerable, but younger managed stands can also be invaded during epidemics (Thatcher et al., 1980). Interest in rehabilitating beetle-killed stands by establishing less susceptible native species such as longleaf pine (*Pinus palustris* Mill.) has prompted restoration and silvicultural research in the southern coastal plain and Florida regions (e.g. Brockway & Outcalt, 2000; Ramsay et al., 2003; Knapp et al., 2006; Haywood, 2007). However, little research on restoration of longleaf pine has been undertaken further inland on the rolling hills of the Piedmont region, spanning several states in south-eastern USA. The term "restoration" is used here in a general sense, referring to rehabilitation of degraded forests or reconstruction of former forest land by reintroducing an underrepresented native tree species.

At one time, longleaf pine stands occupied an estimated 24 million ha in the south-eastern USA (Stout & Marion, 1993). Fire suppression, timber harvest and land conversion have reduced their extent, with less than 5% remaining today (Outcalt & Sheffield, 1996). Longleaf pine ecosystems are fire-adapted and support a species-rich understory plant community when ground fires are frequent (Peet & Allard, 1993). Longleaf pine seedlings undergo a gradual transition from the grass stage to become woody saplings (Boyer, 1990). This is thought to be an adaptation to frequent fire and a unique strategy for reoccupying disturbed sites that gives the slower growing shade-intolerant longleaf pine a competitive

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ISSN 0282-7581 print/ISSN 1651-1891 online
DOI: 10.1080/02827581.2010.485821

advantage over less fire-hardy pines and hardwood competitors (Outcalt, 2000). In the absence of fire, longleaf pine's characteristic grass stage presents a challenge to restoration: height growth is postponed before emergence from the grass stage, and competing vegetation quickly overtops the seedlings. Hardwoods such as sweetgum (*Liquidambar styraciflua* L.) are widespread, prevalent and vigorous competitors that resprout after disturbance. Loblolly pine seedling regeneration, grasses and vines also develop quickly to occupy growing space in the warm humid southern climate. Successful restoration of longleaf pine ecosystems will depend on some form of disturbance to release seedlings from competition, and later to promote natural regeneration in mature stands that would otherwise be succeeded by shade-tolerant hardwoods.

Fire is a useful tool for longleaf restoration, but it may not carry in areas with insufficient quantity or quality of fuels, and it may not be appropriate or acceptable on some ownerships. Similarly, while chemical weed control with herbicide has proven effective in longleaf pine restoration studies on the coastal plain (Brockway & Outcalt, 2000; Ramsay et al., 2003; Knapp et al., 2006; Haywood, 2007), these methods may not be appropriate or acceptable on some ownerships (e.g. near streams, in sensitive ecological areas, or on or near organic farms). Mechanical weed control methods have also been tested, with results inferior to chemical weed control (Knapp et al., 2006). It is unlikely that one weed control method will be most appropriate on all sites (i.e. different fire, herbicide or mechanical treatments may be most effective on sites with different weed problems). Therefore, field experiments that only compare effects and interactions between a limited number of weed control treatments can lack generality.

An alternative research approach with results that would be of greater generality would involve quantifying and comparing the effects of above- versus below-ground weed competition on longleaf survival and timing of emergence from the grass stage. Findings from such a study could then be used to design site-specific weed control prescriptions using any suitable tools and methods acceptable to the landowner. Such results would also be of fundamental interest to ecologists. A basic understanding of the effects of above- and below-ground competition—altered by mechanical weed control (above-ground only) and chemical weed control (above- and below-ground) treatments—could lead to the development of predictive models for use by practitioners. This would require testing different levels of above- and below-ground competition, in terms of both amount and timing of weed competition, potentially necessitating implementation of very large field experiments. Longleaf establishment studies have typically been large in scale, comprising contiguous fixed-area plots arranged in replicated experimental designs; treatments have involved the use of forestry herbicides, prescribed fire treatments, and heavy machinery for mechanical site preparation and weed control treatments (e.g. Brockway & Outcalt, 2000; Ramsay et al., 2003; Knapp et al., 2006; Haywood, 2007).

The short-term study described herein was more modest in scale, using non-contiguous single-tree plots in a randomized complete block design with multiple treatment levels, nested in a split-plot arrangement within contiguous fixed-area treatment plots, designed to study the response surface of above- and below-ground competition on longleaf seedling survival and early growth. The objective was to implement a compact field experiment designed to evaluate restoration treatments, presenting the design as an economical option for monitoring and scientific investigation, and informing practitioners involved in longleaf pine restoration at the Hitchiti Experimental Forest and in the Piedmont region of the south-eastern USA. Specifically, the study sought to address the following questions: (1) How did early weed competition and first year chemical and mechanical weed control treatments affect survival of planted longleaf pine seedlings and their emergence from the grass stage? (2) Under chemical weed control, how did the size of the controlled area around the seedlings affect survival and emergence from the grass stage?

Materials and methods

Study site

The study was conducted at four sites located in the 1900 ha Hitchiti Experimental Forest (33°2′ N, 83°42′ W) in Jones County, Georgia, USA. The forest is near the northern limit of longleaf pine's historical natural range (Eyre, 1980) in a highly modified and degraded environment. Presettlement forest cover was cleared for agriculture by early settlers in the late eighteenth and early nineteenth century. Much of the fertile yet erodible mineral soil was lost over the following century. Widespread land abandonment followed, and trees naturally reoccupied the vacant growing space. Loblolly pine and a mixture of hardwoods were most successful and came to dominate (Brender, 1952). Some of these stands remain today, while others have been harvested and replanted with loblolly pine, forming even-aged stands with naturally regenerating hardwoods.

Throughout the Hitchiti Experimental Forest, patches of even-aged mixed pine–hardwood stands were killed in 2007 by southern pine beetles. The kill areas were burned after the salvage harvest in 2007, consuming most of the scattered woody debris and residual hardwoods. Fire failed to carry through some areas owing to a lack of fuels. Hand planting of containerized 1–0 "mountain variety" longleaf pine seedlings in late March 2008 only deviated from the prescribed 3.65×3.65 m (740 stems ha^{-1}) spacing to avoid less suitable microsites (e.g. stumps and debris). The objectives of restoring longleaf pine were to increase the diversity of conifer species in the forest, evaluate the performance of longleaf pine on degraded Piedmont forest land, and more generally to expand the restricted geographical extent of this once-widespread iconic species.

Switchgrass (*Panicum virgatum* L.) seed was broadcast over most areas, but was not easily distinguishable from other herbaceous and woody weed cover reoccupying the sites after harvesting and burning. Vegetation naturally regenerating throughout the study sites consisted primarily of hardwood stump sprouts and root suckers, vines, forbs and various grasses. Natural regeneration of 22 tree species was recorded, including an abundance of dogwood (*Cornus florida* L.), loblolly pine, persimmon (*Diospyros virginiana* L.), sweetgum and water oak (*Quercus nigra* L.). Five shrub species, 49 forb species and eight vine species were recorded. The most common forb was American burnweed (*Erechtites hieracifolia* (L.) Raf.). Muscadine grapevines (*Vitis rotundifolia* Michx.) were abundant at the four sites selected as experimental replicates for the restoration study.

The elevation of the four study sites ranged from 120 to 150 m a.s.l. Soils were classified as a mixture of Davidson and Vance soil series with remnants of loamy surface layer over clay subsoil (Brender, 1952). Narrow gullies incised the rolling hills. Site 1 was located on a gently sloping south-west-facing upper slope in a 16 ha kill area; site 2 was located on a steeper north-east-facing slope in a 9 ha kill area; site 3 was located on a gentle east-facing slope in a 1.6 ha kill area; and site 4 was located on a grassy hilltop in an 11 ha kill area. Sites 1, 2 and 4 were classified as site index 24.4 m, and site 3 was site index 27.4 m at base age 25 years for loblolly pine (Clutter & Lenhart, 1968). At the time of beetle attack in 2007, the loblolly pines were 24 years old at sites 1 and 2 and approximately 100 years old at sites 3 and 4.

The climate in the forest is described as humid and warm in summer months, and cool in winter. Monthly average low temperatures range from -1°C in January to 19°C in July, and monthly highs range from 13°C in January to 32°C in July, with a record high of 40°C in July 1986 and a record low of -20°C in January 1985. The average annual rainfall of 1180 mm is distributed throughout the year; March is the wettest month with 140 mm, and October the driest with 70 mm average monthly rainfall (www.weather.com).

Experimental design

One experimental replicate comprising four main treatments was established in each of four beetle-killed areas (study sites) dispersed across the forest. The four main treatment plots within each replicate contained 25×25 m square measurement plots surrounded by 4 m wide buffers. Sixteen steel corner posts marked measurement plot corners at each of the four study sites. A colored pin flag was planted beside each longleaf pine seedling within measurement plots and buffer strips, securing a numbered steel tag at ground level. Treatments applied to the main fixed-area plots were mechanical weed control, chemical weed control (repeated in two plots) and control (i.e. no weed control) (Figure 1).

In a split-plot arrangement, each measurement plot (considered the experimental unit for main treatments) was divided into approximately 12 replicate blocks of single-tree plots where a single longleaf pine seedling became the experimental unit within a split-plot replicate of three adjacent seedlings. Three "spot size" spray area treatments were applied to the split-plots (single longleaf pine seedlings) in each replicate within the square fixed-area chemical weed control treatment plots (Figure 2).

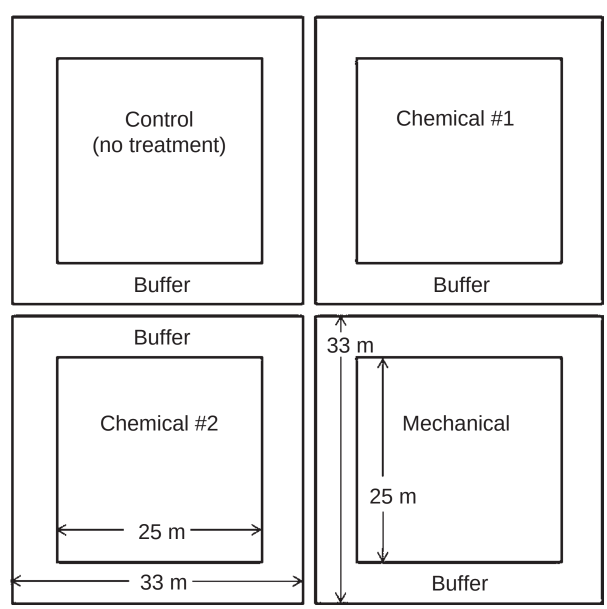

Figure 1. Schematic diagram of one experimental replicate consisting of four treatment plots containing 25×25 m square measurement plots surrounded by 4 m wide buffer strips. Treatments were chemical weed control repeated in two plots, mechanical and control (no treatment).

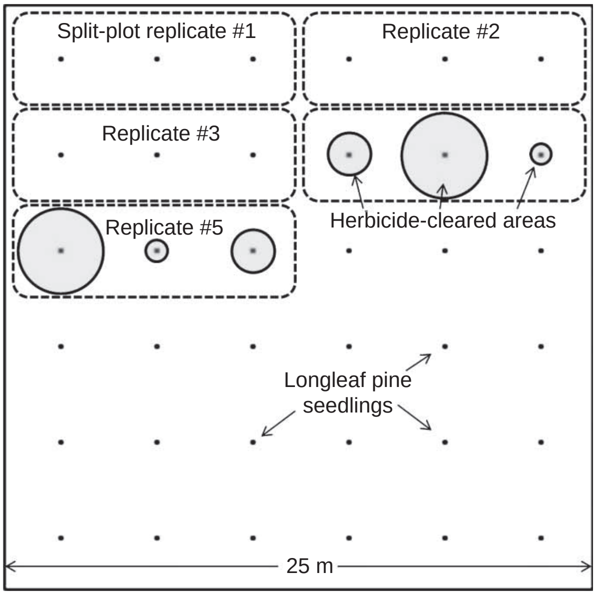

Figure 2. Measurement plot for chemical weed control treatment. Small, medium and large spot sizes of herbicide-cleared area randomly assigned within each replicate of spot size treatments applied to single-tree plots nested within the square 625 m^2 (0.0625 ha) fixed area measurement plot. Longleaf pine seedlings planted on approximately 3.65 × 3.65 m spacing.

Chemical and mechanical treatments were applied approximately 3 months after planting in late June 2008. The objective of the chemical weed control treatment was to reduce above- and below-ground competition in the vicinity of longleaf pine seedlings. Glyphosate in the form of isopropylamine salt of *N*-(phosphonomethyl) glycine was delivered using a backpack sprayer with 2% active ingredient in water at a rate of 6.9 liters active ingredient in 360 liters of solution per ha (D'Anieri et al., 1990). Longleaf pine seedlings were covered with large paper cups before spraying. One week after glyphosate application, competing vegetation was mowed close to ground level, and cut stumps of woody species were immediately treated with an 8% triclopyr water-based solution of triethylamine salt (5.74% triclopyr acid equivalent).

The chemical weed control treatment was applied around each longleaf pine seedling in one of three sizes of circular "spot treatments": the smallest spot size had radius 0.455 m covering 0.65 m^2 ground area; medium spot size was 0.892 m radius covering 2.5 m^2; large spot size was 1.784 m radius covering 10 m^2. The small, medium and large spot size treatments were assigned randomly within replicates of three adjacent longleaf pine seedlings. Mowing in the chemical weed control treatment plots extended beyond the circular spots to cover the entire plot area to reduce above-ground competition uniformly. Vegetation in the mechanical treatment plot was also mowed close to ground level manually using motorized brush saws.

Before treatment in late June 2008, the following data were collected in all 25 × 25 m measurement plots: longleaf pine seedling status (live/dead), physical condition (sparseness of live foliage, damaged/covered), total height (if emerging from grass stage), herbaceous cover percentage within 30 cm of each longleaf seedling (0.3 m^2 area), maximum height of herbaceous cover within 30 cm of longleaf seedling, vine cover percent within 50 cm of longleaf seedling (1 m^2 area), woody vegetation cover percentage within 50 cm of longleaf seedling, maximum height of woody vegetation within 50 cm of longleaf seedling, and number of woody stems within 50 cm of each longleaf seedling. The location of individual longleaf pine seedlings in each measurement plot was mapped on an x, y coordinate system. Survival was also assessed at the end of the first growing season, in October 2008. This did not include assessment of competing vegetation owing to seasonal discrepancies in cover caused by loss of leaf area among annuals and deciduous perennials.

The vegetation assessments were repeated in late June 2009, 1 year after the first assessment and the first set of weed control treatments was applied. All competing vegetation within 50 cm of each longleaf pine seedling was assessed. Vegetation was not assessed in single-tree plots where longleaf seedling mortality was recorded at the previous vegetation assessment. Immediately after the year 2 assessment, chemical weed control was reapplied to the second chemical treatment block (chemical 2) at each study site. The mechanical weed control treatment was repeated at each study site, reducing above-ground competition from herbaceous vegetation, vines and woody perennials in the measurement plot and surrounding buffer. Mowing was also applied under the chemical 2 treatment, completing reduction of above- and below-ground competition in year 2. No treatments were applied to control plots or one of the two chemical weed control plots at each study site (chemical 1).

Analysis

A logistic regression model was developed to predict the probability of longleaf seedling survival as a function of competing vegetation assessed 3 months after planting. The mixed model with binary response variable included fixed effects (competing vegetation) and random effects (study sites, measurement plots). A second logistic regression was developed for end-of-growing season survival data collected in October 2008. This model described effects of treatments (chemical, mechanical) on probability of longleaf pine seedling survival from the time of treatment in year 1 until the end of the first growing season. Mixed models were also developed to predict probability of longleaf survival from the time of treatment in year 1 until the time of assessment and treatment in year 2 as a function of weed control treatments, and as a function of competing vegetation assessed in year 2.

The probability of survival based on size of herbicide-cleared area was also modeled with logistic regression, with a categorical fixed effect (spot size) and random effects (study sites, measurement plots and replicate blocks of three single-tree seedling plots). This analysis was restricted to data for longleaf pine seedlings alive in late June 2008 at the time of chemical treatment. The response variable for the first mixed model was longleaf pine survival at the end of the first growing season. Probability of survival from late June 2008 until the time of assessment and treatment in late June 2009 was the response variable in the second mixed model of spot size and longleaf pine survival.

Logistic mixed models were developed to predict probability of longleaf pine emergence from the grass stage: first, as a function of weed control treatment; secondly, as a function of competing vegetation assessed in year 2; and thirdly, as a function of herbicide spot size in chemical treatment plots. These analyses were restricted to data for longleaf pine seedlings that had not yet emerged from the grass stage at the time weed control treatments were applied in year 1.

Data for competing vegetation were transformed to reduce skewness in data distributions. Models were fitted using the procedure for generalized linear mixed models PROC GLIMMIX of SAS statistical analysis software (SAS Institute, 2004; Littell et al., 2006).

Results

Longleaf pine seedling survival in each main measurement plot averaged 82.5% over the first growing season. During that time, 2.5% of seedlings had emerged from the grass stage and began height growth. Mortality was low between the time of assessment in October 2008 and June 2009, while an additional 10.7% of seedlings had emerged from the grass stage during that period. Woody vegetation assessed 3 months after planting was highly variable in extent and had reached a height of 40 cm on average, although some stems were almost 2 m height. Vine cover was also heterogeneous and low in extent on average. Herbaceous vegetation was more extensive, covering an average of 31% of ground area near longleaf pine seedlings in 2008 and 35% in 2009. Herbaceous vegetation (grasses and forbs) varied widely in terms of maximum height in 2008 and 2009 (Table I). In total, 105 species of

Table I. Summary data for longleaf pine seedling survival since planting and emergence from grass stage in each main treatment plot ($n = 16$), and competing vegetation in single-tree plots around each longleaf pine seedling in the first and second growing seasons, at Hitchiti Experimental Forest, Georgia, USA.

Variable	*n*	Mean	SD	Min.	Max.
Longleaf survival					
June 2008 (%)	16	92.0	7.2	77.1	100.0
October 2008 (%)	16	82.5	10.2	57.1	93.8
June 2009 (%)	16	81.5	9.6	57.1	93.8
Longleaf emergence					
June 2008 (%)	16	2.2	2.2	0.0	7.9
October 2008 (%)	16	2.5	2.2	0.0	7.9
June 2009 (%)	16	13.2	11.4	0.0	42.9
Vegetation in 2008					
Woody cover (%)	607	8.4	11.4	0.0	75.0
Woody max. height (cm)	461	40.2	29.2	0.0	190.0
Vine cover (%)	607	7.7	11.3	0.0	70.0
Herbaceous cover (%)	607	31.4	22.7	0.0	97.0
Herbaceous max. height (cm)	580	45.7	29.7	0.0	185.0
Vegetation in 2009					
Woody cover (%)	521	12.4	18.6	0.0	100.0
Woody max. height (cm)	355	55.3	37.0	2.0	220.0
Vine cover (%)	520	10.4	14.3	0.0	70.0
Herbaceous cover (%)	521	34.8	24.6	0.0	97.0
Herbaceous max. height (cm)	517	53.9	24.7	5.0	160.0

flora were identified in the year 1 botanical survey of the four study sites.

The stature and relative abundance of competing vegetation changed over time in control plots and were affected by weed control treatments. The maximum height of competing vegetation was low within herbicide spots; outside these spots, stature was comparable to vegetation in the mechanical treatment plots and inferior to vegetation maximum height in the untreated control plots. The chemical treatment in year 1 had a lasting impact on vegetation surrounding each longleaf pine seedling: at three study sites, woody and herbaceous cover had not returned to pretreatment cover levels 12 months after the vegetation was sprayed and mowed. Chemical weed control virtually eradicated woody vegetation within herbicide-treated spots. These areas were gradually being recolonized by herbaceous vegetation, and infrequent vines and woody vegetation generally originating outside the treated area and encroaching laterally. The mechanical treatment resulted in an increase in herbaceous and vine cover at all sites, and increased woody cover at three sites. In the untreated control plots at each site, the percentage cover of all vegetation types increased while the proportions of each type changed in favor of woody vegetation (Figure 3).

Vegetation effects on survival

The logistic mixed effects model of longleaf pine survival 3 months after planting indicated that herbaceous vegetation (grass and forb) competition was affecting survival. Woody vegetation cover and height, and vine cover were not significantly affecting early survival of longleaf pine, and were excluded from the final model. From the total number of observations ($n = 628$), a subset of data where herbaceous cover was noted ($n = 580$) entered the logistic model of herbaceous vegetation impacts on longleaf pine survival over the first half of the first growing season. The negative coefficient for herbaceous cover indicated that mortality increased with increasing cover percentage. A positive coefficient for maximum height of herbaceous vegetation suggested that the presence of taller grasses and forbs was associated with greater survivorship (Table II). Model predictions indicated that early survivorship was most impacted by higher cover levels of herbaceous vegetation with shorter stature (Figure 4).

Treatment effects on survival

Neither chemical nor mechanical treatments had a significant effect on first year survival ($p = 0.14$), although survival was higher on average in all treated plots compared with untreated control plots ($p = 0.06$). Survival varied between sites, and by treatment type at each site. Site 3 had less competing vegetation than the other three sites and had high survival rates. Site 1 was the driest and most exposed site, and survival was lowest on average and greatly enhanced by control of competing vegetation. Very little mortality was recorded in the second growing season (Figure 5).

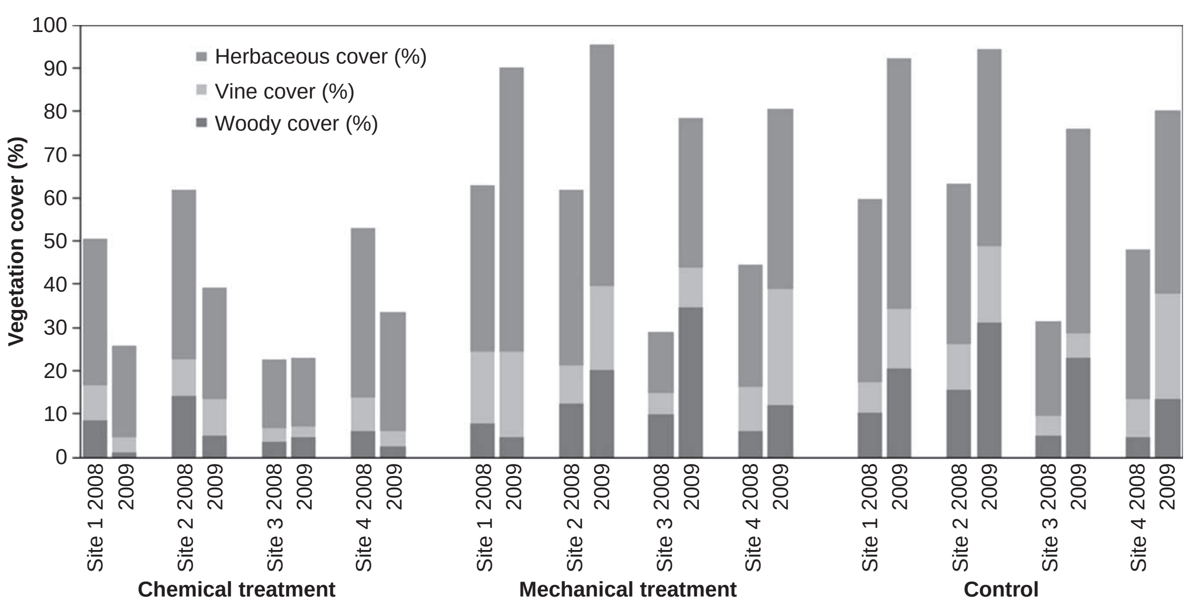

Figure 3. Percentage cover of herbaceous vegetation, vines and woody vegetation surrounding longleaf pine seedlings before and after treatment. Vegetation was assessed immediately before chemical and mechanical vegetation control treatments applied 3 months after planting (2008) and assessed 12 months later (2009) in treated plots and untreated control plots at each study site, at Hitchiti Experimental Forest, Georgia, USA.

Table II. Coefficients and fit statistics for logistic mixed effects model of longleaf pine survival 3 months after planting as a function of herbaceous vegetation cover (%) and maximum height (cm) in all plots at all study sites, at Hitchiti Experimental Forest, Georgia, USA.

Model component	Data	Parameter	Coefficient	SE	df	*t* Value	$Pr > \|t\|$
Fixed effects	June 2008	Intercept (β_0)	0.2713	0.874	3	0.31	0.7765
		Herbaceous cover (β_1)	−0.0294	0.008	571	−3.72	0.0002
		Ln herbaceous height (β_2)	0.9325	0.277	571	3.36	0.0008
			No. groups	Estimate	SE		
Random effects		Study site	4	0.0898	0.1615		
		Plot	4	<0.0001	<0.0001		
Model		$n=580$; $\chi^2=568.4$					

Notes: No. groups = number of data groups for each nested parameter, e.g. four plots nested within four study sites; SE = standard error for coefficient, or measure of variation attributed to random effect parameter; df = degrees of freedom; n = number of observations; χ^2 = generalized chi-square for model.

Logistic mixed model coefficients for treatment effects on survival at the end-of-growing season represented difference in survival between chemical or mechanical weed control treatments and the control (no treatment). On average, survival was greatest among longleaf seedlings receiving chemical weed control and lowest in untreated control plots. However, an *F* test of fixed treatment effects ($F=1.1_{2,571}$, $p=0.33$) and *t* tests of differences in survival between individual treatments indicated that weed control treatment effects were not significant.

A logistic mixed model of treatment effects was also developed with year 2 survival data, giving similar results: no significant differences in longleaf pine seedling survival between weed control treatments implemented in year 1. Mixed models of competing vegetation effects on survival between the time of treatment in year 1 and the time of assessment 1 year later in year 2 did not reveal any significant impacts of vegetation assessed in year 2 on longleaf pine survival.

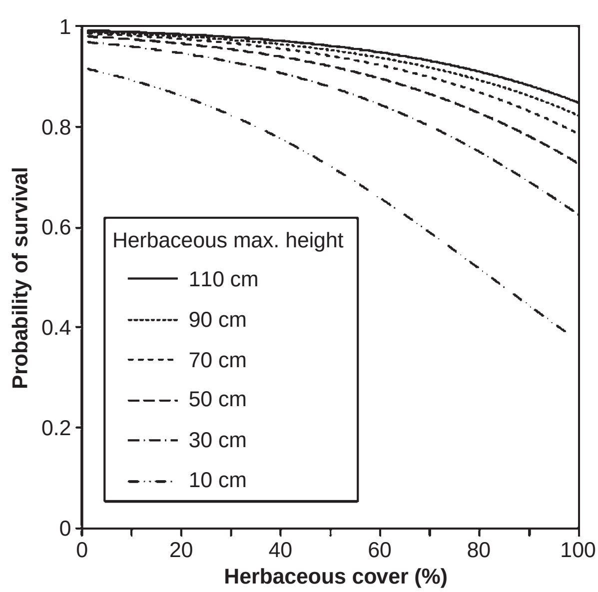

Figure 4. Influence of percentage cover and maximum height of herbaceous vegetation on predicted probability of longleaf pine survival 3 months after planting. Logistic mixed-effects model fitted to data for all plots at all study sites, at Hitchiti Experimental Forest, Georgia, USA.

Herbicide spot size effects on survival

Herbicide spot size treatment (small, medium, large) was included as the fixed effect in a logistic regression of longleaf pine seedling survival in chemical weed control treatment plots at the four study sites. Random effects were split-plot replicate ($n=104$ replicates), plot and study site. Survival from the time of chemical treatment in year 1 until the end of the first growing season was greatest among longleaf seedlings treated with the smallest spot size, and

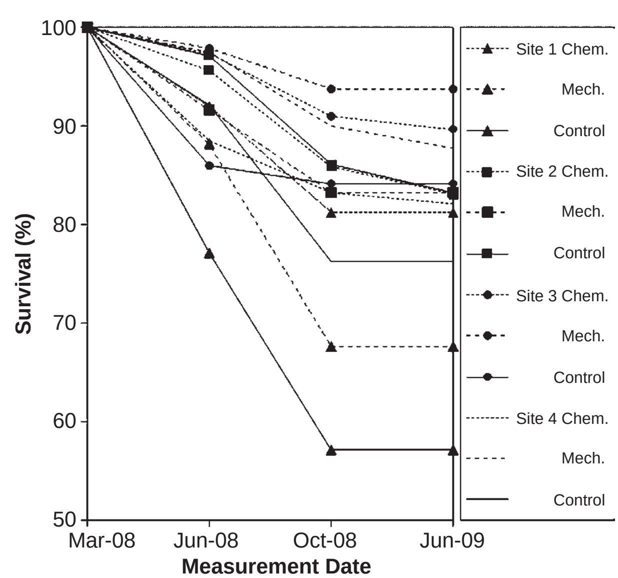

Figure 5. Longleaf pine survival from the time of planting in March 2008 until June 2009 in chemical (Chem.) and mechanical (Mech.) treatment plots and untreated control plots at each study site, at Hitchiti Experimental Forest, Georgia, USA.

least in the largest treated spots, but differences were not significant ($F = 1.3_{2,264}$, $p = 0.27$).

The same result was obtained when survival from the time of treatment in year 1 until the time of assessment 1 year later in 2009 was modeled as a function of herbicide spot size ($F = 0.9_{2,272}$, $p = 0.42$). Replacing the categorical spot size variable with continuous variables spot radius or spot area gave similar results: longleaf pine seedling survival from the time of treatment until the end-of-growing season or until the year 2 assessment decreased with increasing spot size, but the effect of spot size on survival was not statistically significant (2008 survival data: spot radius $p = 0.11$, spot area $p = 0.12$; 2009 survival data: spot radius $p = 0.19$, spot area $p = 0.20$).

Vegetation effects on emergence

The probability of longleaf pine seedling emergence from the grass stage was modeled as a function of competing vegetation assessed in the second growing season. The logistic mixed effects model of longleaf pine emergence over the 12 month period between the time of treatment in year 1 (3 months after planting) and the time of assessment in year 2 (15 months after planting) indicated that woody vegetation cover, herbaceous cover and vine cover were all affecting longleaf pine emergence. The maximum heights of woody and herbaceous vegetation were not significantly affecting longleaf pine emergence and were excluded from the final model. Negative coefficients for percentage cover of all competing vegetation types indicated that probability of emergence decreased as adjacent vegetation cover increased (Table III). Model predictions for different levels and combinations of competing vegetation cover indicated that herbaceous vegetation cover had the greatest impact on probability of emergence, and woody vegetation cover had the least impact. For example, probability of emergence decreased by 3.5% (from 11.3% to 7.8%) when herbaceous cover increased by 20% (from 10% to 30%) while holding constant both woody and vine cover at 10%. In contrast, probability of emergence decreased by only 2.4% (from 11.3% to 8.9%) when woody cover increased by 20% (from 10% to 30%) while holding constant both herbaceous and vine cover at 10% (Figure 6).

Treatment effects on emergence

Logistic mixed model coefficients for treatment effects (fixed effects) on longleaf pine seedling grass stage emergence represented differences in probability of emergence under chemical or mechanical weed control treatments and in control plots (no treatment). Probability of emergence over the 12 month period between the time of treatment in year 1 and the time of assessment in year 2 was 16.5% following chemical weed control, 4.9% following mechanical weed control and 3.6% in control plots. Probability of emergence was significantly greater following chemical weed control treatment than in control plots ($p = 0.001$). Emergence following the mechanical treatment was greater than in untreated control plots on average, but this difference was not significant ($p = 0.60$) (Table IV).

Herbicide spot size did not affect probability of emergence from the grass stage. There were no significant differences in probability of emergence within 12 months of treatment among live seedlings in small, medium and large herbicide spot sizes within the chemical treatment plots at all four study sites ($p = 0.79$).

Table III. Coefficients and fit statistics for logistic mixed effects model of the probability of longleaf pine seedling emergence from grass stage between 3 and 15 months after planting as a function of woody vegetation cover (%), vine cover (%) and herbaceous cover (%) assessed 12 months after year 1 weed control treatments in all plots at all study sites, at Hitchiti Experimental Forest, Georgia, USA.

Model component	Data	Parameter	Coefficient	SE	df	t Value	$Pr > \|t\|$
Fixed effects	June 2009	Intercept (β_0)	−0.2169	0.479	3	−0.45	0.6813
		Ln woody cover (β_1)	−0.2453	0.106	496	−2.32	0.0209
		Ln vine cover (β_2)	−0.3145	0.119	496	−2.65	0.0084
		Herbaceous cover $^{0.5}$ (β_3)	−0.1750	0.066	496	−2.65	0.0083
			No. groups	Estimate	SE		
Random effects		Study site	4	0.3350	0.3473		
		Plot	4	<0.0001	<0.0001		
Model		$n = 506$; $\chi^2 = 437.4$					

Notes: No. groups = number of data groups for each nested parameter, e.g. four plots nested within four study sites; SE = standard error for coefficient, or measure of variation attributed to random effect parameter; df = degrees of freedom; n = number of observations; χ^2 = generalized chi-square for model.

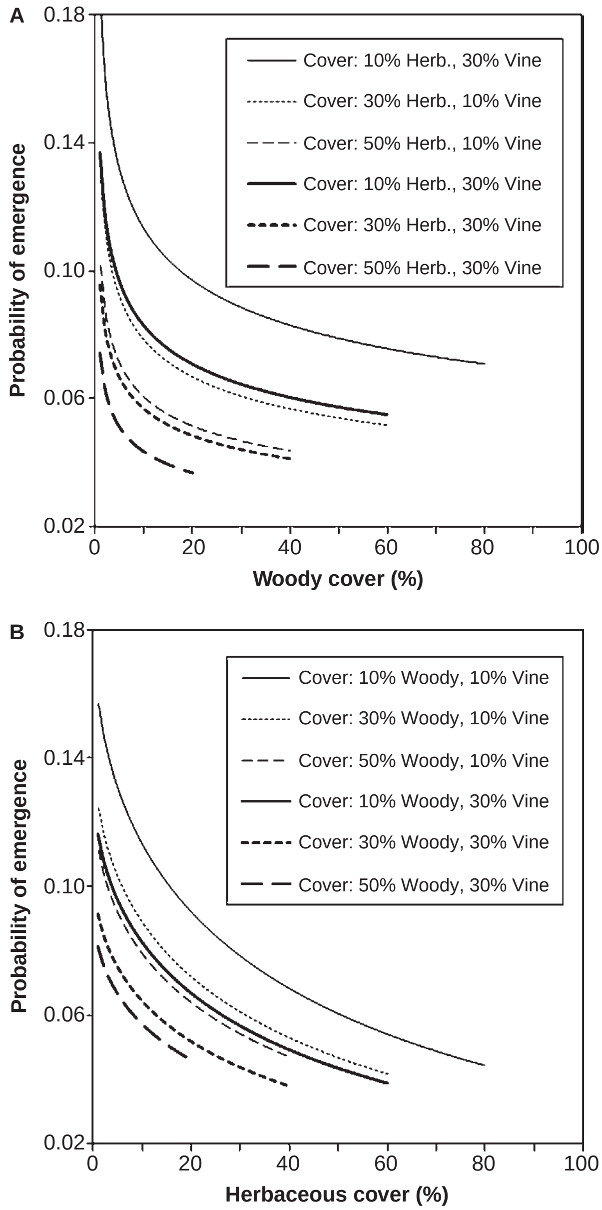

Figure 6. Influence of different combinations of competing vegetation cover on predicted probability of longleaf pine seedling emergence from the grass stage, for a range of (A) woody cover and (B) herbaceous cover up to 100% total vegetation cover. Logistic mixed-effects model fitted to data for 12 month period between the time of treatment in year 1 (3 months after planting) and the time of assessment in year 2 (15 months after planting) in all plots at all study sites, at Hitchiti Experimental Forest, Georgia, USA.

Discussion

At the Hitchiti Experimental Forest, the four study sites were broadcast burned the year before planting, reducing but not completely removing competing vegetation. Three months after planting, herbaceous vegetation assessed within 30 cm of each longleaf pine seedling was found to affect early survival (Figure 4). This result suggested that some form of weed control at the time of planting may be advisable. Increased early survivorship of longleaf pine seedlings in the presence of taller grasses and forbs (Table II) may have been a result of shading and shelter. Longleaf pine survival within the smallest herbicide spot size was greatest on average, perhaps also due to partial shading and shelter from vegetation surrounding the small cleared area. However, differences in survival between herbicide spot sizes and between the main vegetation control treatments were not statistically significant.

Removal of above- and below-ground competition using herbicides and mowing significantly enhanced emergence of longleaf pine seedlings from the grass stage (Table IV), and will probably enhance survival beyond year 2. The increase in competing vegetation cover and its stature in untreated control plots, and the rapid response of all vegetation types in the 12 months following mechanical control (Figure 3) had left longleaf pine seedlings overtopped and generally carrying less foliage than seedlings receiving direct light following chemical weed control. Reapplying mechanical treatments in year 2 gave seedlings in these plots renewed access to light, but the vigorous response of competing vegetation to mowing in year 1 suggested that below-ground competition will continue to increase as available growing space becomes fully occupied. Overall, the results suggested that longleaf pine seedlings exhibit tolerance to shade while in the grass stage, but they may succumb to excessive below-ground competition, or their subsequent development and emergence can be retarded by competing vegetation. Various forms of above- and below-ground competition affect the survival and growth of planted longleaf pine seedlings (Harrington et al., 2003) and other pine species (e.g. Richardson et al., 1996*b*; Amishev & Fox, 2006).

The 3.65 m planted spacings allowed space for herbicide spot treatments up to 1.8 m radius (i.e. 3.6 m diameter) applied to single-tree plots nested within the square fixed-area plots. Single-tree plots are efficient because they minimize effects of site variations and were appropriate because competition between adjacent planted trees was not expected for several years; the interest was in short-term effects of competing vegetation during establishment. Smaller plots allow testing of several treatments in a smaller area (Richardson et al., 1996*a*). A total of approximately 600 trees was sampled across the four replicate sites. The large square fixed-area measurement plots were permanently demarcated with steel corner posts, and seedling locations mapped, for long-term monitoring. In these plots, different silvicultural treatments such as pruning, thinning, fertilization or prescribed burning may be superimposed

Table IV. Coefficients and fit statistics for logistic mixed effects model of longleaf pine emergence from grass stage for the 12 month period following weed control treatment in year 1 as a function of chemical and mechanical vegetation control treatments (dummy variables) in all plots at all study sites, at Hitchiti Experimental Forest, Georgia, USA.

Model component	Data	Parameter	Coefficient	SE	df	t Value	$Pr>\|t\|$
Fixed effects	June 2009	Intercept (β_0)	−3.2812	0.60	1	−5.47	0.1151
		Chemical	1.6607	0.51	606	3.25	0.0012
		Mechanical	0.3195	0.62	606	0.52	0.6036
		Control	0.0000	–	–	–	–
			No. groups	Estimate	SE		
Random effects		Study site	4	0.5942	0.5443		
		Plot	4	0.0671	0.1641		
Model		$n=613$; $\chi^2=544.0$					

Notes: No. groups = number of data groups for each nested parameter, e.g. four plots nested within four study sites; SE = standard error for coefficient, or measure of variation attributed to random effect parameter; df = degrees of freedom; n = number of observations; χ^2 = generalized chi-square for model.

in a factorial design at a later date. The timing of these treatments may be offset to account for different rates of longleaf pine development attributed to effects of early treatments controlling competing vegetation.

Covering the longleaf pine seedlings while spraying protected the young seedlings but was time consuming. The covers also shielded competing vegetation immediately adjacent to the seedlings. Occasionally this vegetation had become intertwined with the longleaf pine's grass-stage foliage and roots, and was difficult to remove after 12 months when treatments were reapplied under the chemical 2 treatment. This problem will persist under the one-time-only chemical 1 treatment and could lead to abrasion and malformation of the longleaf pine if it emerges from the grass stage beneath woody vegetation. In these cases, additional weeding is advisable. However, considering the significant benefit of year 1 chemical treatment on emergence from the grass stage (Table IV) and the low overall rate of seedling mortality in year 2 (Table I), the one-time-only control of above- and below-ground competition in year 1 may be the most economical option for rapid restoration of longleaf pine on beetle-killed forest sites with prolific regeneration of competing vegetation.

The authors caution against interpreting the lack of significant differences in early survival between treatments as justification for establishing longleaf pine in the absence of weed control. The use of herbicides may not be necessary if longleaf pine seedlings survive early grass competition, but repeated mechanical vegetation control treatments will probably be needed to allow seedlings to emerge successfully from the grass stage and overtop their competitors. Prescribed fire may be the most viable alternative to chemical weed control, but will not be feasible or acceptable on some ownerships. Historically, frequent low-severity ground fires controlled competition from woody vegetation in longleaf pine stands, maintaining open stand conditions amenable to longleaf pine regeneration and allowing a diverse range of herbaceous vegetation to persist (Peet & Allard, 1993; Outcalt, 2000). Restoring self-sustaining longleaf pine stands in the Piedmont region of the south-eastern USA will certainly require some form of competing vegetation management to create and maintain conditions favorable for the establishment of longleaf pine and its native herbaceous understory associates (Harrington et al., 2003).

Acknowledgements

Support was provided by the USDA Forest Service Southern Research Station Center for Disturbance Science, the Georgia Forestry Commission and the Humboldt State University Sponsored Programs Foundation. John Moore planned and managed the site preparation and tree planting operations, assisted in study design and planning, and provided logistical support and valuable advice on mechanical and chemical weed control. David Combs performed the botanical survey, and provided extensive technical support and field assistance. Field assistance was also provided by Rex Dagley, Eric Everett, Aaron Green and Greta Langhenry.

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