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Proceedings of the 14th Biennial Southern Silvicultural Research Conference

Edited by
John A. Stanturf

Athens, Georgia
February

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Preface

The 14th Biennial Southern Silvicultural Research Conference was held February 26–March 1, 2007 at the Classic Center, Athens, GA. This conference was the latest in a series of meetings designed to provide a forum for the exchange of research information among silviculturists, researchers, and managers. Presentations emphasized research in carbon, pine and hardwood silviculture, invasive species, wildlife, and growth and yield. Two field trips focused on pine productivity, hardwoods, water quality, wetlands restoration, and wildlife management. The conference was attended by over 200 people. Nine sessions included 100 oral and 62 poster presentations.

Sponsors for the conference included the University of Georgia, Warnell School of Forestry and Natural Resources; Consulting Foresters of America, Inc.; National Association of Professional Forestry Schools and Colleges; National Hardwood Lumber Association; Society of American Foresters; Association of Research Directors; 1890 Land-Grant Universities; and the USDA Forest Service, Southern Research Station. The steering committee devoted numerous hours to reviewing abstracts, establishing the program for oral and poster presentations, and making all necessary arrangements for the conference. Steering committee members included:

David Moorhead (Local Arrangements Chair)
University of Georgia, Warnell School of Forestry and Natural Resources,Tifton, GA
David Dickens, Dick Daniels, Larry Morris and Ron Hendricks, University of Georgia, Warnell School of Forestry and Natural Resources, Athens, GA
Kristina Connor, USDA Forest Service, Southern Research Station, Auburn, AL
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Dave Haywood, USDA Forest Service, Southern Research Station, Pineville, LA
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Marty Spetich, USDA Forest Service, Southern Research Station, Hot Springs, AR
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Susan Cohen, USDA Forest Service, Southern Research Station, Research Triangle Park, NC
Chris Maier, USDA Forest Service, Southern Research Station, Research Triangle Park, NC
Norman Davis, Anderson-Tully, Vicksburg, MS
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Scott Roberts, Mississippi State University, Mississippi State, MS
Michael Blazier, Louisiana State University, Homer, LA
Shep Zedaker, Virginia Tech, Blacksburg, VA
Gordon Holley, Louisiana Tech, Ruston, LA
Lori Eckhardt, Auburn University, Auburn, AL
Chris Allen, Louisiana State University, Baton Rouge, LA
John Kush, Auburn University, Auburn, AL
John Groninger, Southern Illinois University, Carbondale, IL
Mike Messina, Texas A&M University, College Station, TX
John Kushla, Mississippi State University, Verona, MS
Masato Miwa, International Paper, Bainbridge, GA
Ed Lowenstein, Auburn University, Auburn, AL
Andy Ezell, Mississippi State University, Mississippi State, MS
Matt Lowe, Temple-Inland, Diboll, TX
Gary Boyd, International Paper, Savannah, GA
Howard Duzan, Weyerhaeuser, Columbus, MS
Marshall Jacobson, Plum Creek, Watkinsville, GA

Partial funding for the conference was provided by the Southern Research Station and the University of Georgia. We gratefully acknowledge the University of Georgia's School of Forestry and Natural Resources for handling fiscal matters and registration. Special thanks to all committee members for invaluable advice; to David Moorehead for coordinating local arrangements; to Lynne Breland for coordinating communications among the Forest Service, the University of Georgia, and the Classic Center and for tracking abstracts and manuscripts; to Patricia Outcalt for creating and updating the conference web page; to Janet Revell, Lynne Breland, and Beulah Sketo for helping with registration; to Rebecca Garner and Catherine Johnston for help with manuscript editing; and to the University of Georgia students who acted as drivers, set up poster boards, and generally helped with arrangements. The many people who contributed to the success of the field trips have our sincere thanks. We also gratefully acknowledge all those who helped judge student presentations and posters.

Special recognition is given to the moderators. They include: Jim Guldin, Mike Messina, Harry Quicke, Bruce Jewell, Hans Williams, Andy Ezell, Marty Spetich, Kristina Connor, Rich Guldin, Brian Oswald, Tom Waldrop, Tom Lynch, Gordon Holley, Callie Schweitzer, Jimmie Yeiser, and Nancy Herbert.

A special feature of this conference was the awarding of student travel scholarships. Individuals were selected for this award based on giving a paper at the conference, recommendation from their institutional sponsor, and willingness to assist with audio-visual duties.

The 113 papers published in these proceedings were submitted by the authors in electronic media. Limited editing was done to ensure a consistent format. Authors are responsible for content and accuracy of their individual papers.

John A. Stanturf
Program Chair
USDA Forest Service
Southern Research Station
Athens, GA

Contents

Carbon

Moderator:

JAMES GULDIN

USDA Forest Service

Southern Research Station

QUANTIFYING CARBON SEQUESTRATION IN FOREST PLANTATIONS BY MODELING THE DYNAMICS OF ABOVE AND BELOW GROUND CARBON POOLS

Chris A. Maier and Kurt H. Johnsen[1]

Abstract—Intensive pine plantation management may provide opportunities to increase carbon sequestration in the Southeastern United States. Developing management options that increase fiber production and soil carbon sequestration require an understanding of the biological and edaphic processes that control soil carbon turnover. Belowground carbon resides primarily in three pools: roots, necromass (litter, roots), and soil. There is little evidence that intensive management affects mineral soil carbon. Conversely, perennial root systems contribute to carbon sequestration through formation of long-lived belowground biomass and carbon in root necromass and woody debris that may persist for years following harvest. Due to their large mass and physicochemical composition, these dead coarse roots require decades to decompose. If the length of the decay process extends beyond the length of the next harvest rotation, it will result in an accumulation of soil carbon. Increasing productivity and shortening rotation length may accelerate carbon sequestration over successive rotations. Further, management activities that retain forest floor and slash material or incorporate organic materials into the soil during site preparation may also increase soil carbon.

INTRODUCTION

Forests are being considered as one option for stabilizing or reducing atmospheric carbon dioxide (CO_2). Forests can reduce atmospheric CO_2 by storing carbon in biomass, soil, and products and can be used as biofuel offsetting fossil fuel (Birdsey and Heath 2001). However, forests grown into perpetuity will provide no long-term CO_2 reduction because eventually carbon losses will equal or exceed carbon gain. Management of forest carbon sequestration should be viewed as a temporary mitigation effort spanning 50 to 100 years as new technologies to store carbon or reduce carbon emissions are developed. Carbon capture in forest growth provides a low cost approach for meeting State and national carbon sequestration goals and can be accomplished with available technology.

Forests will likely never be managed solely for carbon sequestration (Johnsen and others 2004). However, the potential economic value of emission credits from carbon sequestration might provide a co-benefit that, depending on financial value, could affect management practices (Birdsey 2006). Intensive pine plantation management may provide opportunities to increase carbon sequestration in the Southeastern United States. An understanding of the biological and edaphic processes that increase and retain soil carbon is required so that management can be modified to increase fiber production and soil carbon sequestration.

MULTIPLE ROTATION CARBON DYNAMICS

Managed forests can provide in-situ (biomass and soils) and ex-situ (products) pools for carbon sequestration (Johnsen and others 2001). Intensive management utilizing improved silviculture, fertilization, and genetically superior planting stock has increased aboveground loblolly pine productivity threefold (Borders and Bailey 2001) and decreased rotation lengths. Less is known about how plantation forestry affects the stand carbon balance (Johnsen and others 2001, 2004). Belowground biomass carbon and fluxes is the weakest link in our understanding of forest carbon cycling. There is little evidence that silviculture and intensive management affects, either positively or negatively, long-term mineral soil carbon (Schlesinger 1990, Richter and others 1999, Laiho and others 2003). This is presumably because of the relatively high decomposition rates of newly input carbon and the low rate of carbon incorporated into organo-mineral complexes (controlled by soil physical properties).

Additionally, most studies have been conducted during the first rotation following the abandonment of agriculture (Richter and others 1999) or soil sampling has randomly or even systematically (Laiho and others 2003 Schlesinger 1990,) avoided regions intimately associated with stumps where decomposition rates of large coarse roots are slower. Thus, given little evidence of the potential of forest management to increase mineral soil carbon, we concentrate here on examining the dynamics of root biomass and necromass and their contribution to belowground carbon storage. Along with aboveground pools, we consider the potential of forest management to provide short- or medium-term carbon sequestration.

In-situ plantation carbon dynamics can be conceived as follows: trees are planted, above and belowground biomass grows over time, trees are harvested, root biomass becomes root necromass, trees are replanted and new biomass is accreted as root necromass decomposes (fig. 1). The varying rates of these processes, the rotation age, silviculture, management, and the period for which these carbon dynamics are assessed all greatly influence the estimate of carbon sequestration. For example, intensive management practices that increase aboveground productivity results in increased belowground carbon in tap and coarse root systems (Albaugh and others 2004, Samuelson and others 2004a). Because of their relatively large mass and physicochemical configuration, these root systems require decades (20 to 60 years) to decompose (Ludovici and others 2002). If the length of the decay process extends beyond the length of the next rotation, it will result in an accumulation

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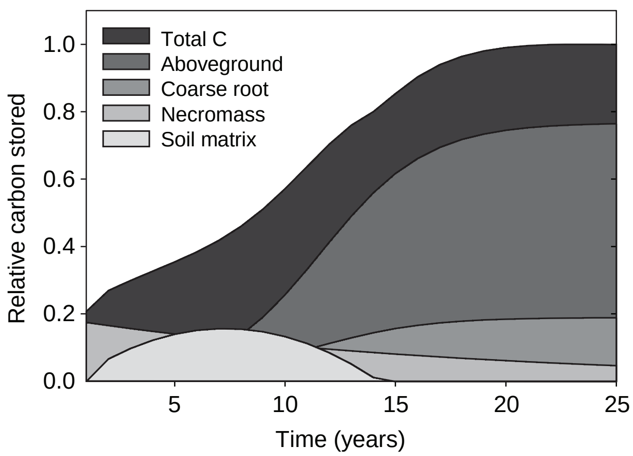

Figure 1—Conceptual changes in carbon storage in a pine plantation in aboveground and belowground pools over a 25-year rotation. Changes in soil matrix carbon reflect changes in the organic matter carbon pool above a baseline.

of soil carbon. Additionally, large increases in soil carbon occur after harvesting, presumably from recently severed root system and decomposing litter (Johnsen and others 2004, Van Lear and others 1995). This pool consists of light fraction carbon or free organic matter that is not physically or chemically bound in organo-mineral aggregates and will not persist through the next rotation. There is evidence that management practices such as fertilization may decrease the rate of carbon loss from this pool (Butnor and others 2003, Pangle and others 2002, Samuelson and others 2004b). While carbon in decomposing root systems and litter is relatively labile compared to recalcitrant mineral soil C, these pools are easily manipulated and may offer an opportunity to increase carbon sequestration in short rotation plantations. Johnsen and others (2004) hypothesized that combining increased aboveground productivity with shorter rotation lengths will increase belowground carbon sequestration over multiple rotations in intensively managed pine plantations.

Here we demonstrate simple examples of stand carbon dynamics to illustrate how intensive forestry and rotation length can potentially alter site carbon storage over successive rotations. We also explore management impacts on carbon sequestration and identify its key drivers as well as the most critical information needed to improve the reliability of estimates across different site types. There are numerous carbon action programs at the global, national, and State levels, and U.S. forests are being registered for potential future carbon credits; however, there is no certified method to estimate forest carbon sequestration. We illustrate what we consider the correct approach to calculate short- to medium-term carbon sequestration in intensively managed forest plantations.

MATERIAL AND METHODS

We empirically modeled loblolly plantation carbon dynamics of four carbon pools: aboveground biomass, coarse roots, root necromass, and soil matrix organic matter (fig. 1). We then compare simulated multiple rotation carbon sequestration for stands receiving different levels of management.

We used stem biomass growth curves developed for a high productivity, short rotation research plantation (Martin and Jokela 2004). In these stands, reducing nutrient limitations through weed control and/or fertilization resulted in dramatic increases in stem production (fig. 2). In addition, alleviating soil nutrient limitations accelerated stand development such that treated stands reached 95 percent of maximum stem biomass about five years earlier (arrows, fig. 2) than non-treated controls.

Aboveground biomass was calculated as a fixed proportion of stem biomass [i.e., AGbiomass=1.52*stem biomass (Albaugh and others 1998)]. Root system biomass was accreted from coarse root allometry shown in Johnsen and others (2004) using data derived from a wide range of sites, stand age, and productivity. Root necromass attenuation was estimated using an empirical model from Ludovici and others (2002). Fine fraction soil organic matter dynamics from 0 to 30 cm were estimated by equations fitted to soil carbon from Johnsen and others (2004) adjusted for initial root necromass estimated at the beginning of each rotation. This pool represents the ephemeral increase in soil matrix carbon above an unchanging baseline. Carbon was estimated by multiplying biomass by 0.5.

Simulations examined carbon dynamics in the various pools over a 60-year project period for three treatment scenarios: no treatment (NT), weed control (WC), and fertilizer plus weed control (FWC) (Martin and Jokela 2004). Treatment effects on carbon sequestration were compared for three 20-year rotations and four 15-year rotations in the case of WC and FWC treatments. We assumed that the site was managed as a loblolly pine plantation prior to the project. Curves for biomass, necromass and organic matter C carbon were calculated as above, the area was integrated under each curve (fig. 1), and the sum of the integrated values was divided by 60 (years) to provide an estimate of mean-integrated carbon stored per year (i.e., Mg C $ha^{-1}yr^{1}$).

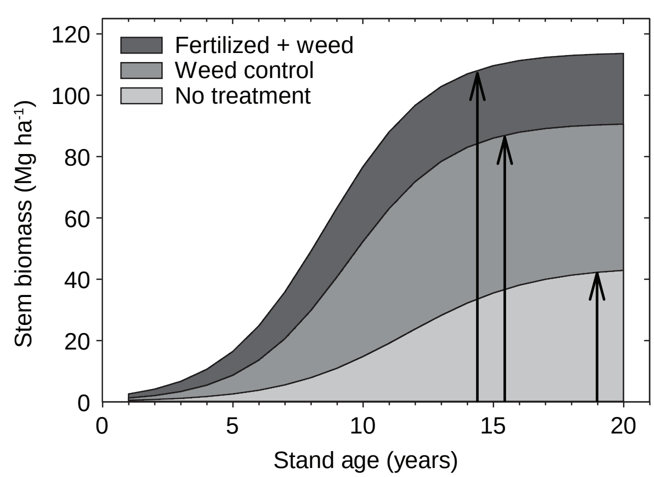

Figure 2—Stem biomass accumulation for three silviculture treatments: no treatment (NT), weed control (WC), and fertilization and weed control (FWC) derived from growth equations (Martin and Jokela 2004). Arrows indicate time when stand reaches 95 percent of maximum stem biomass.

RESULTS

Total carbon accumulation in the NT scenario approached 45 Mg C ha^{-1} in each of the three successive 20-year rotations (fig. 3a). In contrast, maximum total carbon accumulation was substantially higher in the WC (data not shown) and FWC (fig. 3b) scenarios and increased over successive rotations. This corresponded to a mean integrated total carbon (above + belowground) of 28.0, 61.9, and 80.7 Mg C ha^{-1} y^{-1} in the NT, WC, and FWC scenarios, respectively, over the 60-year period (table 1). Root necromass increased over time in the WC and FWC scenarios because root decomposition exceeded the rotation length (fig. 4a). The WC and FWC stands maintained 10.7 and 16.3 Mg C ha^{-1} y^{-1} more belowground carbon, respectively, than did the NT over the project period (table 1). Decreasing rotation length resulted in less accumulated total carbon in the WC and FWC (fig. 3c) stands and 10 to 12 percent less total mean-integrated carbon maintained on site (table 1). However, shorter rotations resulted in an increase in belowground carbon accumulation (fig. 4b), in mean integrated belowground carbon storage, and in carbon of harvested biomass (table 1). Thus, while the longer rotation length increased the total mean integrated carbon storage; shorter rotations resulted in increased belowground carbon storage and carbon stored in harvested biomass.

DISCUSSION

These scenarios demonstrate that stand productivity and rotation length potentially can influence in-situ carbon storage over successive rotations in short-rotation pine plantations (e.g., pulpwood, biomass for energy). Weed control and/or fertilization, greatly increased aboveground production and resulted in increased belowground carbon sequestration in living coarse root systems, necromass, and soil organic matter. Furthermore, while longer rotation lengths had higher mean-integrated total in-situ carbon storage, increased productivity combined with shorter rotations resulted in more belowground carbon storage and carbon in harvested biomass. This is due to increasing the overlap in accumulation of new biomass and the loss of necromass and soil organic matter through decomposition. These scenarios illustrate the importance of these ephemeral carbon pools (root necromass and organic matter) in the carbon budget of intensively managed plantations.

The most limiting aspect of these calculations all involve estimates of belowground carbon allocation and residence times. Ludovici and others (2002) estimated loblolly pine taproot decomposition from a chronosequence beginning with a 60-year-old plantation. Short rotation, high-productivity plantations have taproots that are chemically dissimilar to older trees and likely decompose at a faster rate under similar soil conditions. We know very little about taproot growth and decomposition processes in plantation forests or the variation in these processes across genotype (species), site conditions, disturbance regimes, and climate. For example, Ludovici and others (2002) examined trees on a well drained Piedmont soil. Loblolly pine plantations along the coastal plain are often planted on moderately to poorly drained sites with high water tables. Even in very high productivity plantations, these sites are often inundated for large portions of the year. Anaerobic conditions reduce initial necromass decomposition rates and probably increase the residence time of root necromass. On the other hand, site preparation activities such as disking, bedding, chopping or burning may accelerate root necromass decomposition during stand reestablishment (Gough and others 2005). Given the importance of the overlap of root biomass growth and root necromass decomposition, realistic estimation of coarse root decomposition is critical for quantifying in-situ carbon sequestration, particularly when rotation length is short.

The simulations ignored carbon stored in perennial hardwood root systems. Hardwoods would be an important carbon component in the NT scenarios. Miller and others (2006) found after 25 years of plantation growth, silviculture practices (chop and burn or shear-pile disk) that increased aboveground pine production had no affect on total coarse root biomass when hardwoods were considered. Thus, we could assume that hardwood biomass would make up most of the difference in mean integrated carbon storage between the NT and WC scenarios. However, Martin and Jokela (2004) found that the WC and FWC increased site carrying capacity, which probably results in increased mean integrated carbon storage. For example, comparing FWC and WC scenarios, fertilization increased mean integrated belowground carbon storage by 25 to 38 percent depending on rotation length.

Table 1—Simulated mean integrated carbon storage over a 60-year project period

Treatment	Rotation	Total C storage	Aboveground C storage	Belowground C storage	Δ BG	Harvested biomass
	years	*Mg C ha^{-1}yr^{-1}*				*Mg C ha^{-1}*
NT	20	28.0	14.8	13.2		197.1
WC	20	61.9	38.0	23.9	10.7	271.8
FWC	20	80.7	51.2	29.5	16.3	340.8
WC	15	54.4	28.0	26.4	13.2	344.0
FWC	15	72.9	39.8	33.1	20.0	438.4

Note: Carbon (C) storage in aboveground, belowground, and harvested biomass are compared for 20-year and 15-year rotations for stands under a range of treatments: no treatment (NT), weed control (WC), and fertilization plus weed control (FWC). Δ BG is the increase in belowground C storage compared to No Treatment.

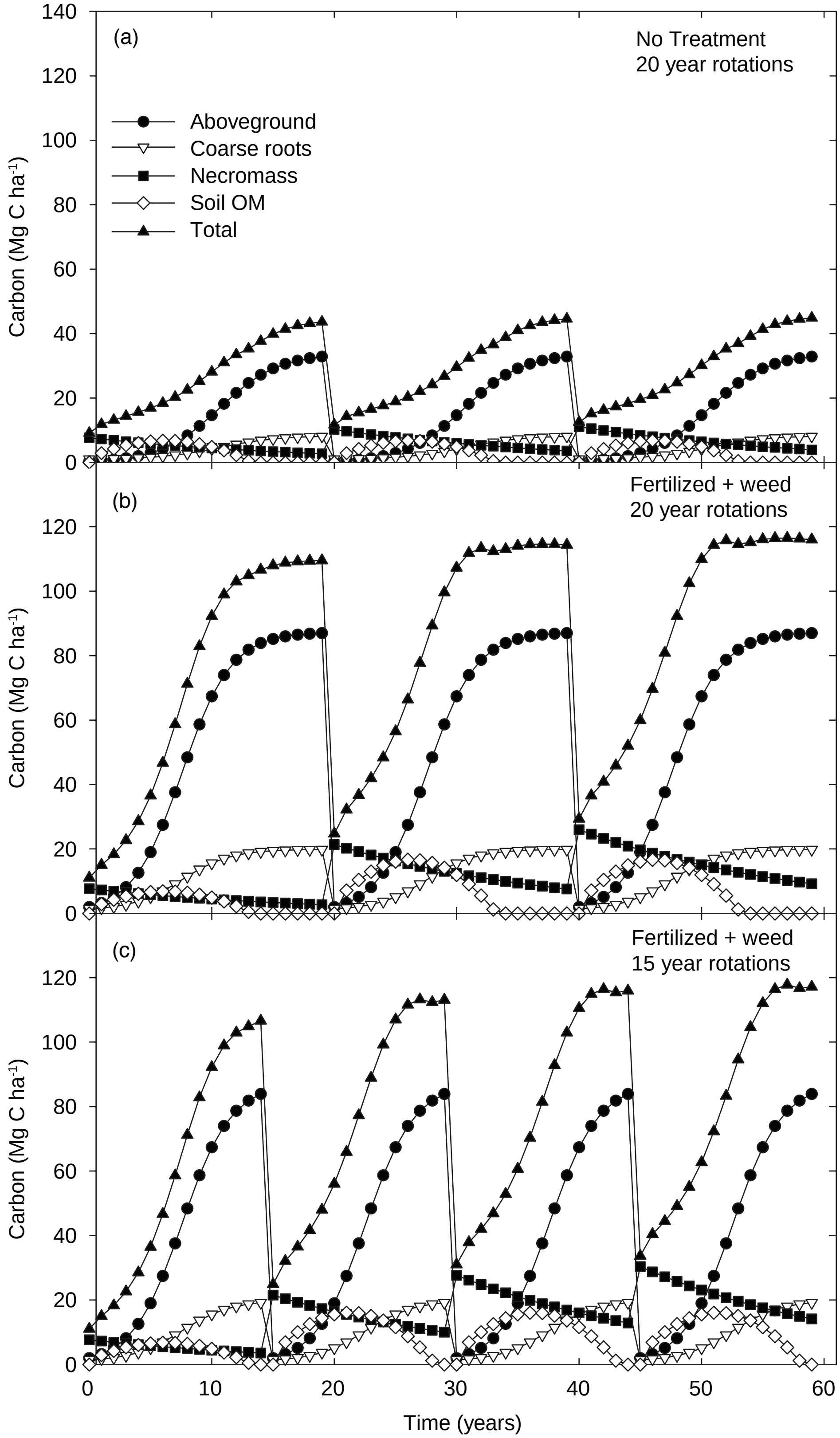

Figure 3—Simulated stand carbon (C) accumulation over three 20-year rotations for stands receiving (a) no treatment (NT) or (b) fertilizer plus weed control (FWC) and (c) over four 15-year rotations for FWC.

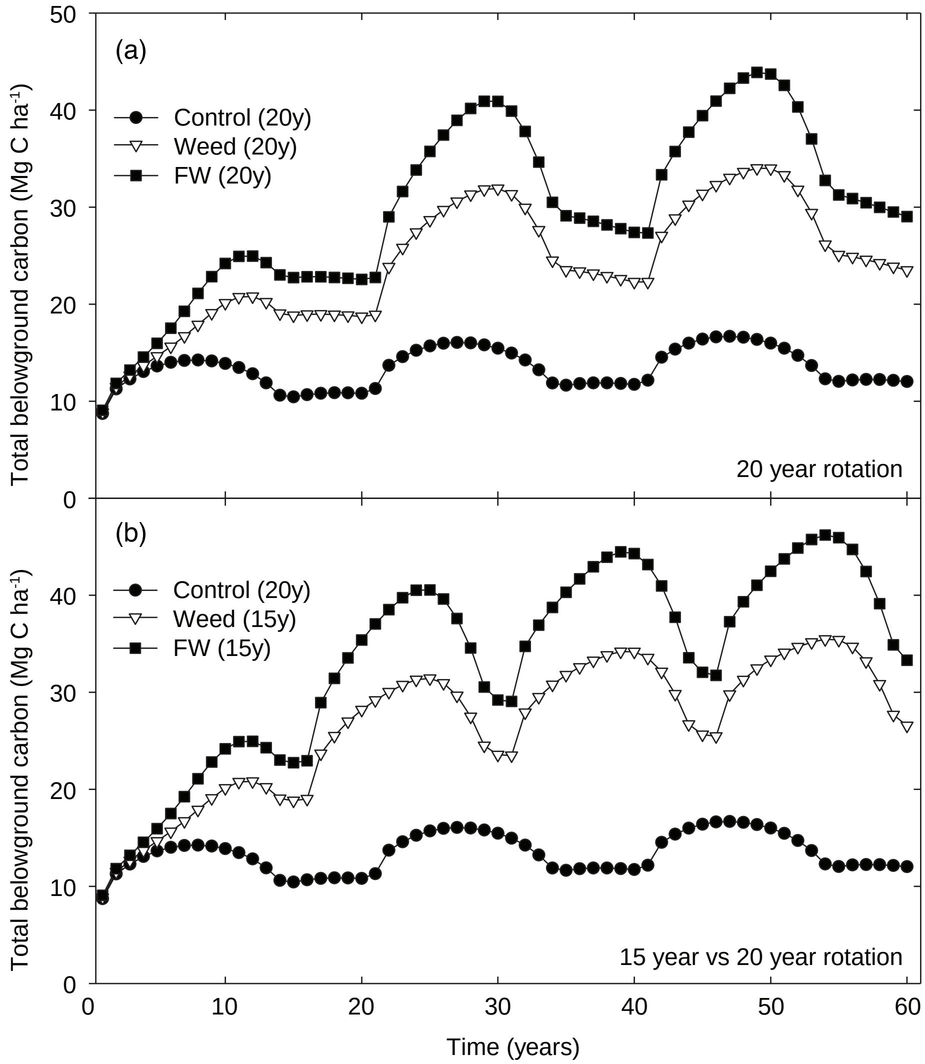

Figure 4—Simulated belowground carbon (C) accumulation for stands receiving either no treatment (NT), weed control (WC), or fertilization plus weed control (FWC). Comparisons show treatment responses for (a) 20-year rotations and for (b) 15-year (WC, FWC) versus 20-year (NT) rotations.

Aboveground carbon allocation was fixed with time and treatment. While aboveground metrics such as total biomass, stem biomass or basal area is a good predictor of coarse root mass (Johnsen and others 2004), root to shoot ratios vary with stand development and site productivity (Albaugh and others 2006) and species. A better understanding of the physiological controls of carbon allocation is needed for modeling short rotation forest carbon budgets.

Although forests in the U.S. are being registered for potential carbon credits, there is no certified method to estimate forest C sequestration. Simple estimates of carbon accumulation based on net carbon stock (e.g., live biomass, mineral soil C) (Birdsey 2006) changes over an interval will not be sufficient for estimating the carbon budgets of short rotation plantations. We suggest that the mean integrated approach that incorporates dynamic changes in soil organic matter and root decomposition following harvesting is the more appropriate method for quantifying site carbon for short rotation plantations. Accounting for site-specific effects on these ephemeral pools will improve the precision of carbon estimates.

CONCLUSIONS

The analyses shown in this study, while informative, are simple and not sufficient to quantify marketable carbon credits. However, we contend our approach is the most valid way to address the problem. Our results suggest that short-rotation; high-productivity forests potentially can be managed for carbon sequestration, and management practices that optimally increase productivity and retard necromass decomposition will provide the greatest carbon sequestration.

Clearly, our ability to quantify coarse root decomposition in young plantations under varied environmental conditions represents our weakest area of understanding and is critical for conducting realistic analyses using our approach.

In addition, mechanistic studies are needed to better understand the variation associated with genotype (within and among species) and G x E interaction in carbon accretion, retention, and loss patterns. Regardless, carbon sequestration will need to be estimated for forests sooner rather than later. The value of C credits should be tied to the precision and accuracy of carbon sequestration estimates (Birdsey 2006, Johnsen and others 2004). Further research should endeavor to improve accuracy of estimates across a broad array of forest conditions.

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CARBON SEQUESTRATION AND NATURAL LONGLEAF PINE ECOSYSTEM

Ram Thapa, Dean Gjerstad, John Kush, and Bruce Zutter[1]

Abstract—The Southeastern United States was once dominated by a longleaf pine ecosystem which ranged from Virginia to Texas and covered approximately 22 to 36 million ha. The unique fire tolerant species provided the necessary habitat for numerous plant and animal species. Different seasons of prescribed fire have various results on the ecosystem and the carbon which is stored in the trees and different vegetation classes. After analysis of the various hardwood treatments and seasons of burn, the basal area of the longleaf pine and the soil carbon amounts differ. These results show that certain seasons of prescribed fire can yield more basal area (winter) and soil carbon (winter). Vegetation classes and the amount of stored carbon are also affected by the season of burn.

INTRODUCTION

Atmospheric carbon dioxide (CO_2) levels have been increasing over the past several decades. As a greenhouse gas, there are concerns that the increased CO_2 levels will cause potentially damaging changes to global climate. Worldwide, there has been increasing attention given to reducing atmospheric CO_2 levels by increasing carbon sequestration and storage, in forested ecosystems. Birdsey and Heath (1997) estimated United States forests have sequestered enough carbon over the past 40 years to offset approximately 25 percent of CO_2 emissions in the United States. According to this report, managed southern forests played a large role in this offset.

Kush and others (2004) presented reasons for longleaf pine (*Pinus palustris* Mill.) being the major southern pine species to consider growing for sequestering carbon. The southeastern United States was once dominated by natural communities of longleaf pine. This longleaf pine ecosystem, which currently covers 1.2 million ha, was historically estimated to have covered 22 to 36 million ha ranging from Virginia to Texas. The ecosystem formed by the fire tolerant longleaf pine is unique because it supports a number of endangered species of plants and animals, such as the pitcher plant and red-cockaded woodpecker. It is also the second most endangered ecosystem in the United States.

Fire is critical to longleaf pine management. What is not known is what role fire will play in sequestering carbon? Preliminary research was begun by using a long-term study conducted by the U.S. Forest Service on the effects of season of burn and hardwood control treatments on understory plant succession and overstory development of longleaf pine. Boyer (1995) reported on response of understory vegetation before, and then seven, and nine years after the treatments. Kush and others (1999, 2000) examined the effects of 23 years of these treatments on the long-term response of understory vegetations.

OBJECTIVES

The experiment was conducted in order to determine the relationship between the different prescribed burn treatments and the above ground biomass and carbon sequestration. The subsurface carbon sequestration of the soil in the longleaf pine ecosystem was also sampled.

METHODOLOGY

The Escambia Experimental Forest (EEF) was used as the site of study. Located in Escambia County, AL, it is managed by the U.S. Forest Service in cooperation with the T.R. Miller Mill Company. The design of the experiment consisted of three treatments using a Randomized Complete Block Design (RCBD) to limit hardwood competition. The first treatment was the use of prescribed fire in a biennial burn. The different seasons for the prescribed burns were winter (December to February), spring (April to May), and summer (July to August). A control treatment of a no burn check was included. The second type of treatment was a chemical treatment using undiluted 2, 4-D with an application rate of 1 mL per 2.54 cm of diameter at breast height (d.b.h.). This herbicide was applied to hardwood species in the late spring of 1973 as the initial and only treatment. The third type of treatment was a mechanical treatment. Mechanical treatments were initially used in 1973 on any stem greater than 1.3 m in height. Future use of the mechanical hand clearing method was used when it was necessary to do so. An untreated check was used as a control for the experiment.

Plot Sampling

The overstory, consisting of longleaf pine, was sampled by measuring d.b.h., crown height, and total height in early September 2003. All hardwood trees having a d.b.h. greater than 1 cm were measured for d.b.h. and total height. All living materials having a d.b.h. less than 1 cm were destructively sampled in nine plots per treatment plot in late September and early October in 2003. The destructively sampled plot size was 0.90 square meters. The various vegetation classes include grasses, vines, herbaceous plants, and woody plants. The litter layer was sampled with a single 30.5 square cm subplot contained in each sample plot.

Soil Sampling

The soil was sampled in each of the nine sample plots at three different depths with a stainless steel probe in early May 2006. Sample depths of 0-10 cm, 10-20 cm, and 20 cm

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and below were used. The slope on the plots was minimal; therefore its influence was small.

Carbon Analyses Protocol

A Thermo Finnigan Flash 1112 Series N/C Analyzer was used to perform the carbon analyses in the different vegetation classes, the litter layer, and the soil.

Statistical Analysis

A two-way analysis of variance (ANOVA) was used in order to determine the statistical significance of the treatments on understory biomass and overstory longleaf pine basal area. The soil carbon was also analyzed by using a two-way ANOVA with the various soil depths as the block variables. The SAS program was utilized to perform the two-way ANOVA (SAS Institute Inc. 2003). All tests were conducted using an alpha of 0.05.

RESULTS AND DISCUSSION

The basal area was the highest in the no burn sample plot (table 1). The summer prescribed fire resulted in the lowest amount of basal area, and the winter fire had the highest amount of basal area. The spring prescribed fire resulted in a basal area which was between the winter and summer fires.

There were no statistically significant differences in the percent of carbon between the hardwood treatments or the season of burn (table 2). However, there was a significant difference in the percent of carbon in the vegetation classes.

The different seasons of prescribed fire resulted in different amounts of stored carbon. For the burn treatments, the winter fire had the highest amount of stored carbon, followed closely by the spring burn (table 3). The summer burn had the least amount of stored carbon. The no burn check treatment contained the highest amount of stored carbon of all the treatments.

The amount of carbon in the vegetation classes and the litter layer varied with the season of burn. The grass had the most carbon with the winter burn and the least carbon in the absence of a burn (table 4). The herbaceous layer had the most carbon in the spring burn and the least carbon in the absence of a burn. The vine layer had the most carbon in the absence of a burn and the least carbon with the summer burn. The woody layer had the most carbon with the spring burn and the least carbon with the winter burn. The litter layer had the most carbon in the absence of fire and the least carbon with the summer burn.

Table 1—Relation of season of burn to basal area

Season of Burn	Basal Area (m^2/ha)
Winter	26.6
Spring	26.1
Summer	25.7
No Burn	27.1

Table 2—Statistical significance for the hardwood treatment, season of burn and vegetation classes

% Carbon	p-value
Hardwood Treatment	0.1985
Season of Burn	0.8604
Vegetation Classes	0.0004

Soil Carbon

The interaction between the hardwood treatments and the seasons of burn was not significant (p-value of 0.733). The supplemental hardwood treatments had no effect on the soil carbon content (p-value of 0.649). However, the season of burn did have a significant effect on the soil carbon content (p-value of 0.0408). A pair-wise comparison of soil carbon and different seasons of burn was performed by using Tukey's Studentized Range (HSD) test, with an alpha value of 0.05. Overall, the mean carbon contents are significantly different among the summer burn and the plot without a burn.

A comparison between the control treatment and the three seasons of burn was performed with Dunnett's t-test. The summer burn and the no burn had significantly different results in the means of the soil carbon content. The plot without a burn had the highest soil carbon percentage. Among the plots with prescribed fire, the spring burn resulted in the highest soil carbon percentage and the summer burn resulted in the lowest soil carbon percentage.

Table 3—Total aboveground biomass for the different seasons of prescribed fire

Season of Burn	Total Biomass (kg/ha)
Winter	359740.0
Spring	353954.3
Summer	339791.3
No Burn	385967.7

Table 4—Amount of carbon present in non-longleaf pine vegetation

Season of Burn	Grass	Herbaceous	Vine	Woody	Litter	Total
	------------------- Vegetation Classes ------------------					
	--------------------- *Kilograms per Hectare* ---------------------					
Winter	54.7	18.1	50.9	113.6	8237.1	8474.4
Spring	36.1	41.4	18.0	570.7	9508.4	10174.6
Summer	28.8	34.7	3.1	141.1	8037.4	8245.1
No Burn	0.9	2.1	187.3	259.9	20761.8	21212.0

CONCLUSION

The sample plot without a burn had the highest amount of basal area and the greatest amount of carbon storage. The winter burn resulted in the greatest basal area and carbon storage of all the plots treated with prescribed fire. There was very little significant interaction between the hardwood treatments and the season of burn.

The season of burn had a significant effect on the amount of soil carbon storage, with the spring burn having the highest amount and the summer burn having the least amount. However, the only truly significant results occurred in relation to soil carbon when the summer burn and the no burn were compared. The no burn plot had the highest amount of soil carbon.

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CARBON SEQUESTRATION RESULTING FROM BOTTOMLAND HARDWOOD AFFORESTATION IN THE LOWER MISSISSIPPI ALLUVIAL VALLEY

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Abstract— Increasing abandonment of marginal agricultural lands in the Lower Mississippi Alluvial Valley (LMAV) and rising global atmospheric carbon dioxide (CO_2) levels create a need for better options of achieving rapid afforestation and enhancing both below and aboveground carbon sequestration. This study examines the responses of six mixtures of bottomland hardwood species to fertilizer and herbaceous release treatments as a means of enhancing afforestation and carbon sequestration in the LMAV. A completely randomized design with 6 x 2 x 2 factorial arrangement of treatments was employed on sites near Cleveland and Greenville, MS. Dormant unrooted cottonwood cuttings and bare-root (1-0) seedlings of all other species were planted in spring of 2006. First-year survival ranged from 50 to 80 percent for red mulberry, green ash/oak mix, NRCS species mix and an oak mix. Cottonwood monoculture and cottonwood/oak mix plantings showed survival below 40 percent. Very little differences in first-year growth were noted among the various planting types. Soil carbon prior to planting constituted more than 99 percent of the ecosystem carbon. We expect a shift and redistribution of carbon pools as the site transitions from herbaceous vegetation to forest.

INTRODUCTION

Growing forests for carbon sequestration is a new concept for an old practice. The need for it is not only driven by the persistent rise in atmospheric carbon dioxide (CO_2) levels (IPCC 2007) but also the increasing extent of valuable forest loss coupled with resultant abandonment of marginal agricultural lands especially in the Lower Mississippi Alluvial Valley (LMAV) (Amacher and others 1998). To expedite the process of carbon sequestration under a forestry scenario, efficient afforestation mechanisms are required. Early afforestation efforts have favored fast-growing monoculture stands as an attempt to achieve rapid carbon sequestration (Nilsson and Schopfhauser 1995). In hardwood plantation silviculture, matching species to the site is essential in achieving successful regeneration and afforestation (Stanturf and others 1998). Stands of fast-growing species play a pivotal role in meeting the rising demand of woody biomass production (Schweitzer and Stanturf 1999), however, the impacts of slow/fast growing hardwood species on below- and above-ground carbon sequestration are not well defined in the Mississippi River alluvial bottomlands. In the LMAV, early reforestation activities primarily focused on pure stands of oaks and pecans for their wildlife value (Stanturf and others 1998), though currently mixed species plantings are being adopted (Schoenholtz and others 2001). While fast-growing monocultures provide a more rapid financial return to land owners and enhance public perception of reforestation efforts (Schweitzer and Stanturf 1999), carbon value, aesthetics and ecological integrity of such forests may be compromised. King and Keeland (1999) questioned the predominance of oaks in pre-settlement bottomland hardwood forests and suggested that the shortage of seedling availability may increase the diversity of future plantings. Establishing native bottomland hardwood species and types based on existing stands of similar soils and site characteristics offer better opportunities of restoring the historic LMAV bottomland hardwood forest and may assure multiple benefits including below- and aboveground carbon sequestration. Planting a variety of bottomland hardwood species may more closely approximate diversity of natural stands and may maximize below- and above-ground carbon sequestration because of the multifunctional characteristics of diverse forest ecosystems. If indeed these stands can thrive under this concept, these stands may prove more socially and ecologically valuable than traditional bottomland hardwood monoculture plantations. However, their ability to mimic succession and answer these questions are beyond the scope this study.

Intensive early silvicultural treatments, including fertilization and herbicide use, can increase the survival and growth rates of planted hardwoods (Baker and Blackmon 1976, Ezell and Shankle 2004) and subsequently aboveground carbon sequestration in hardwoods. Because of past agricultural practices nitrogen (N) can be a limiting nutrient on LMAV soils protected by the levee system. Herbaceous competition is a major challenge to bottomland hardwood afforestation in the LMAV (Groninger and others 2003). Fertilization and herbaceous release practices in young afforested bottomland hardwood stands may boost success, but effects on below- and aboveground carbon sequestration are not well understood. Fertilization can affect other soil processes such as respiration, microbial activity, and soil pH (Lee and Jose 2004), thus potentially affecting net carbon sequestration on such afforested sites.

New and efficient silvicultural techniques will enhance afforestation establishment success, restore the ecological integrity of degraded lands, enhance carbon sequestration and meet the multiple objectives of landowners in the LMAV. Benefits of afforesting marginal lands in LMAV may include wildlife habitat restoration, connecting fragmented bottomland forest, sequestering carbon thereby providing carbon credits for land owners, as well as restoring many other valuable biogeochemical and hydrologic functions (Shoenholtz and others 2005). This study is designed to test the performance of a number of hardwood species mixtures under early herbaceous release and fertilizer application treatments on

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two sites in the LMAV. Specific objectives are 1) to compare survival and growth performance of the different species mixtures after one growing season, 2) to examine the survival and growth response of different species mixtures to fertilizer application and herbaceous weed control and 3) to assess the trends of initial below-and above-ground carbon prior to afforestation.

MATERIALS AND METHODS

Study Sites

The study was conducted at two sites in the LMAV: 5 miles west of Greenville, MS (33°48'N, 90° 98'W) in Washington County and 5 miles north of Cleveland, MS (33°74'N, 90°73'W) in Bolivar County. The climate is typically warm and humid. The original vegetation cover was temperate deciduous bottomland hardwood forest. Mean annual temperature is 17 °C, with winter and summer averages of 6 °C and 28 °C, respectively. Mean annual rainfall is 1430 mm. Effects of small elevation changes on species survival and development have been reported (Hodges and Switzer 1979). The soils are alluvial in origin; dominant soil types are Commerce silt loam (Fine-silty, Mixed, Superactive, Nonacid, Thermic Fluvaquentic Endoaquepts) and Forestdale silty clay loam (Fine, Smectitic, Thermic Typic Endoaqualfs) on the Greenville and Cleveland sites, respectively (Morris 1961, Rogers 1958). Both sites have been in pasture for at least the past 25 years although the Greenville site supported row-crop agriculture prior to conversion to pasture.

Treatments

A 6 x 2 x 2 factorial arrangement of treatments in a completely randomized design with 3 replicates was used on each site. Six types (levels) of bottomland hardwood (BLH) species mixtures (table 1), two levels of fertilizer (fertilizer and no fertilizer) and two levels of herbicide (herbicide and no herbicide) were used in the study. Nitrogen, Phosphorous and Potassium (NPK) fertilizer (15:10:5) planting tablets were applied to fertilizer treated plots, one tablet in a separate hole adjacent to each planted seedling. Goal®2XL was applied at a rate of 64 ounces per acre with Latron AG-98 at 0.25 percent vol. /vol. to control herbaceous weeds 2 and 5 months after planting. Goal®2XL was applied over the top of seedlings with a band width of about 0.5 m using an ATV mounted sprayer. Minor budbreak had occurred in seedlings at the first application in early April. At the time of the second application however, most seedlings had developed good foliage. The herbicide was intended to serve as herbaceous release for the woody crops and the fertilizer to provide immediate nutrient requirements soon after establishment of all planting stock. Bare-root (1-0) seedlings for all species, except cottonwood which were dormant un-rooted vegetative cuttings, were planted in January-February 2006 at a spacing of 3 by 3 m. The experimental unit was a quarter-acre plot with an average of 108 seedlings planted per plot. Initial heights and root collar diameters were measured prior to planting. Seedling survival, height and groundline diameter were measured every third month after planting. Subsequent growth data were based on a random sample of 25 percent of seedlings per plot. When plot survival decreased below 25 percent, whole plot monitoring was employed for the last set of data during the first growing season.

Initial soil carbon and above-ground carbon were determined prior to planting. Soil samples to a depth of 100 cm were collected using Oakfield probes and 7.4 cm diameter by 3.7 cm height cylinder core samplers. Each 100 cm core sample had 3 replicates per plot, partitioned into four depths: 0–15 cm, 15–30 cm, 30–60 cm, 60–100 cm. Replicates for each depth were composited, dried to a constant weight at a temperature of 70 °C and ground and analyzed for soil total nitrogen (N) and total carbon (C) using a Fisons NA1500 elemental analyzer at the Mississippi State Forest and Wildlife Research Center (FWRC). Core-sampled soils were oven dried at 105 °C to a constant weight and the dry weight used to estimate the bulk density of the soil by depth for each plot. Bulk density data were used to estimate soil C on a per-hectare basis. Herbaceous data were collected using 0.5 by 0.5 m square quadrats with three replicates randomly located in each plot. All live biomass within a quadrat was removed and oven dried at 65–70 °C. Dry weights were determined and the amount of carbon estimated as half the dry weight per plot of herbaceous biomass (Vogt 1991). This constituted the initial above-ground carbon.

Mean change in height and diameter per plot relative to mean height and diameter at planting were estimated after the final measurements were made. Percent survival was also estimated relative to number of seedlings planted. Plot means of survival, height, and diameter were subjected to analysis of variance (ANOVA) using SAS and, where appropriate, significant means were ranked according to Fishers' Protected LSD test at P = 0.05. Herbaceous carbon changes over time and soil carbon changes with depth were compared using paired t-test at a significance level of alpha = 0.05.

RESULTS

Survival and Growth

Survival was analyzed to determine the effects of the different species combinations on the two test sites. First-year survival was approximately 56 percent on the Cleveland site and 45 percent on the Greenville site. On the Cleveland site, green ash/oak mixture and red mulberry monoculture stands had the highest survival at 75 percent and 72 percent, respectively. Survival of the oak mixtures and the NRCS species mixtures were slightly above 60 percent but not significantly different. Cottonwood monoculture and cottonwood/oak mix plots had the lowest survival of 17 percent and 48 percent respectively (table 2). Fertilizer and herbicide treatments at the Cleveland site had significant effects on survival (table 3). Survival of the only fertilizer treated plots were 15 percentage points lower than the control (no fertilizer, no herbicide treated plots). No significant differences were observed between the control, herbicide, and fertilizer+herbicide combined (interaction). Similar trends in survival were observed on the Greenville site with respect to species mixtures. Red mulberry monoculture had the highest percent survival rate (72 percent). No significant differences were observed between the green ash/oak mixture and the NRCS species mixtures (table 2). Oak mixed plots, cottonwood/oak mixture and cottonwood monoculture showed survival of less than 50. No significant differences were observed in survival on the Greenville site with respect to fertilizer and herbicide treatments (table 3).

Table 1—Six types of bottomland hardwood species mixtures planted on marginal agricultural lands on Greenville and Cleveland test sites in MS

Treat-ment #	Planting Type	Stock type	Species Mixture/Combination
1	Monoculture	Unrooted Cuttings	Cottonwood (*Populus deltoides* Bartr. ex Marsh)
2	Monoculture	Bare-root seedlings	Red mulberry (*Morus rubra* L.)
3	Mixture	Bare-root seedlings	Oak mix: 33% Nuttall (*Quercus texana* Buckl.), 33% Willow (*Q. phellos* L.) and 33% Water oak (*Q. nigra* L.)
4	Mixture	Unrooted Cut-tings & Bare-root seedlings	50% Cottonwood and 50% Oak mix (Nuttall, Willow and Water)
5	Mixture	Bare-root seedlings	50% Green ash (*Fraxinus penn-sylvanica* Marsh.) and 50% Oak mix
6	Mixture	Bare-root seedlings	NRCS: [50% Nuttall, 20% Green Ash, 30% Sycamore (*Platanus occidentalis* L.), Persimmon (*Diospyros Virginiana* L.), Willow and Water oak]

On the two sites, first-year survival of red mulberry monoculture and NRCS species mixtures were approximately the same. Of the remaining species combinations, survival was relatively better at the Cleveland site compared to the Greenville site. On the Cleveland site, the green ash/oak mixed plots exhibited the highest survival rate of 75 percent which was 25 percent better than on the Greenville site (table 2). Mean survival differed slightly for NRCS species mix, red mulberry and oak mixture, at the Cleveland site and for NRCS, red mulberry and Green ash/oak mix at the Greenville site. Mean survival of 15 percent and 37 percent were observed for the cottonwood monoculture and cottonwood/oak mix respectively (table 2). Mean survival for the oak mix, cottonwood/oak mix and cottonwood monoculture was respectively 58, 91, and 30 percent higher at the Cleveland site.

One-year growth in diameter and height were significantly different among species combinations on both sites. Growth in height and diameter in cottonwood monoculture stands were 72 cm and 5 mm, respectively. Little or no change in height and diameter was apparent for all other species mixture a year after establishment on both sites (table 4). Fertilizer-herbicide combined treatment yielded significantly greater growth especially in diameter in the Forestdale soils of Cleveland than the other three treatments (table 3). No significant difference in growth was observed on the Greenville site with respect to fertilizer and herbicide treatments (table 3).

Below- and Aboveground Carbon

Initial aboveground carbon estimated from the existing herbaceous vegetation prior to planting did not differ by site. However, seasonal differences were significant (fig. 1). The average aboveground carbon in May was approximately 3600 kg/ha, this decreased by about 700 kg/ha in the latter part of summer (August). Initial below ground data revealed that soil nitrogen (fig. 2a) and soil carbon (fig.2b) concentrations tended to decrease with depth on both sites. Soil nitrogen and carbon differed significantly by site in the upper 15 cm layer but tended to be similar in the deeper layers at $P = 0.05$. Nitrogen and carbon values within the top 15 cm soil layer were about 1 mg-N/g soil and 17 mg-C/g soil greater than values within the 15–30 cm subsurface layer on the fine textured Cleveland soils. On the coarse textured soils of Greenville, mixed differences were observed in soil N concentrations, where the highest N concentration was in the 15–30 cm layer (fig.2a). Below the 15 cm layer, soil C did not differ significantly with depth on the Greenville Commerce silt loam soils; soil C was however, 5 mg-C/g soil greater in the surface 15 cm layer. Soil bulk density ranged from 1.1 to 1.2 g/cm^3 for all soil depths except for surface soil-densities of Cleveland which had soil-density as low as 0.7 g/cm^3. At the ecosystem level, above-ground biomass represented

Table 2—Mean survival of bottomland hardwood species mixtures following one growing season on Cleveland and Greenville sites. Values followed by the same letter in the same column are not significantly different at P = 0.05

	Mean Survival (%)	
Species	Greenville (GV)	Cleveland (CL)
Cottonwood (CW)	12.70 e	16.50 d
Red mulberry	71.90 a	71.70ab
Oak mix	40.10 c	63.30 b
CW/Oak mix	25.20 d	48.20 c
Green ash/oak mix	58.40 b	75.30 a
NRCS spp. mixes	61.90ab	62.20 b

less than one percent of the total ecosystem carbon on both Cleveland and Greenville sites (table 5). Below ground C indicated that 54 percent of Cleveland soil C accrued in the upper 30 cm layer at the Cleveland site while 44 percent C occurred in the same layer of the Greenville site (table 5). Total ecosystem C was more than 1 kt/ ha greater at the Cleveland site compared to the Greenville site.

Table 3—Chemical treatment effects on first year mean survival, change in height and diameter on two sites in the LMAV. Values in the same column followed by the same letter are not significantly different at P = 0.05 for each site

Treatment	Height (cm)	Diameter (mm)	Survival (%)
Cleveland			
Control	8.30ab	0.96b	63.40a
Fertilizer	8.73ab	1.28b	48.50b
Herbicide	4.26b	0.73b	57.40ab
Fertilizer+ Herbicide	16.81a	2.67a	55.50ab
Greenville			
Control	6.35a	0.60a	45.40a
Fertilizer	7.68a	0.82a	45.80a
Herbicide	11.24a	1.14a	50.00a
Fertilizer+ Herbicide	3.90a	1.02a	39.00a

DISCUSSION

Survival and Growth

Survival and growth of bottomland hardwood species are influenced by several factors ranging from seedling quality/handling to environmental factors (Stanturf and others 1998). Success of bottomland hardwood afforestation has varied with site preparation (Lockhart and others 2003), species type (Stanturf and others 2000), soil type, planting stock/method (Stanturf and others 1998), and competition control (Ezell and Catchot 1998). In general, a survival of 247–494 seedlings/ha or 50–80 percent at age three is considered successful among restorationists in the LMAV (King and Keeland 1999). While (Allen 1990) reported successful hardwood afforestation at 266 stems per acre (665 stems/ha), the Natural Resources Conservation Service (NRCS) standard for successful afforestation is a minimum of 247 stems/ha of acceptable species after 3 years of establishment (Stanturf and others 2001). Although, the 50–80 percent survival rate shown by most of the species mixtures (red mulberry, NRCS, green ash/oak mix and the oak mix) in this study (table 2) should have been higher, they are within reported limits for successful afforestation. The wide variations in survival on both sites may be among other variables an indication of species preference for site. Red mulberry and NRCS species mixtures appear to be better adapted to both site conditions but the inconsistencies in survival of the other species combinations may be due to factors such as drought, herbivory, noxious and persistent herbaceous species competition, planting stock quality, handling, planting conditions as well as edaphic site factors.

Rapid early growth in height for bottomland hardwood species is essential to overcoming difficult site conditions (Stanturf and others 2000). Common site conditions impacting hardwood survival and growth include; flooding, restrictive pans, competing vegetation, drought, herbivory, soil pH levels and presence of vines (Stanturf and others 2000, Stanturf and others2004). Correctly matching species to soil/site conditions may ensure high survival and continued growth. However, rapid early growth of species such as cottonwood or slow early growth of oaks may not necessarily indicate long-term adaptability of a particular species to site. Soil-site characteristics tied to species needs for long-term growth is key to successful establishment. Survival and growth trends observed in this study may be attributed to a number of these site factors. First-year growth in height changed only slightly for all of the species mixtures. The two monoculture treatments showed opposite growth patterns. Cottonwood monoculture had a 71–74 cm increase in height with 6 mm increase in diameter while red mulberry monoculture stands decreased by 25 cm in height relative to the initial height at planting. The survival of cottonwood in this study is similar to the findings of (Randall and Krinard 1977) who noted first year survival of unrooted cuttings to be 36 percent. First-year growth of cottonwood in this study was however far below the 8-9 feet height and 3.1 inches diameter growth by Randall and Krinard (1977). The poor survival and growth of cottonwood in this study is probably due to a combination of factors such as poor quality of cuttings, improper handling prior to planting, genetics and site relationship as well as several factors discussed elsewhere in this paper. Lack of first-year growth and decline

Table 4—Initial and first-year mean diameters and heights of six bottomland hardwood species mixes on two sites in the LMAV. Values followed by the same letter in the same column are not significantly different at P = 0.05

Species	Diameter (mm)			Height (cm)		
	Initial	First year		Initial	First year	
		Greenville	Cleveland		Greenville	Cleveland
Cottonwood (CW)	3.11	8.92a	8.93a	5.25	78.90a	76.93a
Red mulberry	4.21	4.24d	4.63d	62.79	31.41c	39.50c
Oak mix	5.66	5.73bc	6.21c	49.24	45.40b	46.00bc
CW/Oak mix	3.39	5.51cd	6.97bc	39.83	47.00b	53.30b
Green ash/ oak mix	7.16	6.79bc	7.74b	50.17	47.60b	51.70b
NRCS spp mixes	6.90	6.99b	7.09bc	49.38	50.10b	46.90bc

in height of the other species mixtures may be explained by the dry site conditions following planting (April-May 2006) and the extended drought season (4.5 months long) of 2006 (National Weather Service 2006), herbivory, competing vegetation and poor seedling quality for some species. Sumerall (2007) observed various intensities of herbivory due to cotton rats and rabbits on the different species mixtures, notably red mulberry, oak mixture, green ash/oak mixtures and NRCS species mix plots on these same sites. Dense herbaceous vegetation reflected in the biomass data (fig.1) during the summer may have further reduced available soil moisture under already drought stressed conditions. Herbaceous vegetation may out-compete the seedlings for nutrients and water from the soil as well as reduce light levels reaching the seedlings resulting in poor survival and growth. In addition, poor root/shoot ratios of seedlings prior to planting might have also contributed to the low survival and poor growth of bareroot seedlings. The distinct decline in heights of red mulberry may be due to the characteristic large shoots compared to roots of the planting stock. Seedlings with poor root/shoot ratios may experience poor survival and first-year growth, especially in drought conditions. The high survival (72 percent) of red mulberry is a result of rapid resprouting from roots. Thus, red mulberry, just like the oaks, may have high coppicing ability and as such under stressed conditions will resort to resprouting allowing the species to be more effective in afforestation situations.

Studies by Ezell and Cachot (1998) and Groninger and others (2003) indicated that use of pre-emergent sulfometuron methyl and post-emergent glyphosate yielded excellent survival and increased growth in some bottomland hardwood species. Using Goal®2XL, we found no significant differences between herbicide and no herbicide treatments in survival and growth (table 3). The lack of significant results suggests that the rates applied were either too low or that there are too many grass species tolerant to Goal®2XL. Hot field temperatures following herbicide application could have caused rapid breakdown of Goal®2XL. Fertilizer application however significantly decreased survival over the control but no significant differences were observed in growth (table 3). Fertilizer uptake in plant roots requires moisture. Lack of moisture in the plant root system due to early droughts possibly created osmotic stress within the rhizosphere of establishing roots leading to seedling wilt and subsequently a decrease in survival. The combined effects of fertilizer and herbicide treatments significantly increased growth perhaps due to the fact that herbaceous competition was somewhat reduced, increasing water and nutrient availability for seedling uptake.

Below- and Aboveground Carbon

Herbaceous biomass constitutes the majority of aboveground carbon in this study. Tree seedling data were not included because previous studies by Zimmermann (2001) on nine year old oak stands indicated less than one percent of the aboveground carbon accrued from trees. Barker and others (1996) noted that grassland provides a substantial C sequestration potential, however afforesting such sites provides seven times greater carbon sequestration than on grasslands. We found approximately 3500 kg/ha carbon in the above-ground vegetation during the active growing season, though this was less than one percent of the total ecosystem carbon (table 5). Above-ground herbaceous vegetation carbon significantly decreased from May to August 2006 (fig.1) indicating that aboveground carbon on grasslands may have rapid turnover rate. The trends in above-ground carbon may be explained by patterns of annual variations in climate.

On abandoned agricultural lands, soil carbon tends to increase steadily subjective to vegetation composition

Table 5—Total ecosystem (kt/ha) carbon of abandoned agricultural lands showing the distribution of C below- and above-ground on two soil types in the lower Mississippi alluvial valley

Soil Type	Depth				
	0-30 cm	60-100 cm	Soil Total	Herbaceous	Total Ecosystem C
Forestdale	4.50	3.80	8.30	0.30	8.30
Commerce	3.10	3.90	7.10	0.30	7.10

(Jobbagy and Jackson 2000, Knops and Tilman 2000), soil texture and climate patterns (Jobbagy and Jackson 2000). On both grass and forested lands, soil C has been reported to decrease with depth (Jobbagy and Jackson 2000, Vesterdal and others 2002). Our results show that soil carbon decreased with depth and was somewhat higher in the finer textured Forestdale soils than coarse textured Commerce soils (fig. 2 and table 5). On Forestdale soils in Lake George, Zimmermann (2001) found 4.1 kt-C/ha soil carbon prior to afforestation in the upper 30 cm surface soils. This is similar to 4.5 kt-C/ha of the Forestdale soils found on the Cleveland site in our study. Differences in soil C in the upper 30 cm layer between Commerce and Forestdale soil may be explained largely by the variations in texture, bulk density and past land use. High soil organic carbon was noted to be associated with fine-textured soils (Jobbagy and Jackson 2000). Low bulk density of 0.6 g/cm^3 on Forestdale soils may account for the higher carbon and nitrogen concentrations in the upper 0–30 cm layer. The lower carbon content in the upper 30 cm of the Commerce soils may be due in part to past agricultural activities and higher efflux of carbon due to increased decomposition. Disturbance due to tillage coupled with the coarse-textured nature of commerce soils may have fueled decomposition processes. On both soil types, soils in the lower 30–100 cm were similar in carbon content (table 5). Bulk density did not differ with depth on the two sites within the 30–100 cm subsurface soils and may explain the similarity in soil carbon beyond the 30 cm depth. Because soils in this area were formed from alluvial deposits, the similarities in soil C at the deeper 30–100 cm layers are very likely. Total site carbon storage includes the mineral soil, ground cover, and vegetative pools (Londo 2000). Total site carbon in our study was 1.2 kt greater in the fine textured Forestdale soils compared to the course textured Commerce soils of the Greenville site (table 5). In their unforested state, finer alluvial soils, with relatively higher clay contents may be better carbon sinks. However, as the vegetation changes from grassland to bottomland hardwood forest, the distribution of ecosystem carbon is unclear. More carbon is likely to be sequestered in the plantation as it ages (Londo 2000). In general, carbon sequestration levels increase as a plantation progresses through time until it reaches maturity.

CONCLUSION

Although it is too early to make any useful recommendations from this study, preliminary results suggest that mixed hardwood species plantings on the Cleveland and Greenville sites are relatively better in survival and growth, than the cottonwood and red mulberry monocultures. Thus, the use of species mixtures provides the advantage of potentially overcoming some difficult site conditions. Planting mixed-hardwood species is an appropriate technique for use in afforestation of marginal lands in the LMAV but species selection is critical to achieving satisfactory results, because different site characteristics and variables affect the performance of different species. Other factors such as seedling quality, handling prior to planting may impact first year survival and growth. Because of seedling problems, no one-monoculture or species mixture is best and additional testing should be done to recommend more viable species combination types. Using a combination of 15:10:5 NPK fertilizer and Goal®2XL as early management practices in bottomland hardwood afforestation on Forestdale soils may be worthwhile during the first year.

On unplanted old fields, above-ground C is a small portion (<1 percent) of total ecosystem carbon. Greater quantities of carbon (3.1-4.5 kt-C/ha) tend to accumulate in the upper 30 cm of the soil but this depends on the physical properties of the soil. Soil carbon tends to be similar for different soils at deeper depths. As the vegetation transitions into a forest, the influence of the species mixes and early management practices should redistribute ecosystem carbon pools and fluxes on these afforested sites.

ACKNOWLEDGMENTS

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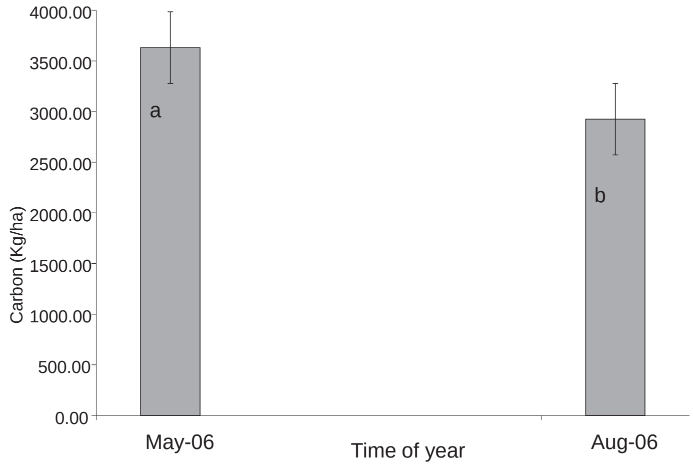

Figure 1—Above-ground carbon at different times of the year on former agricultural lands at the LMAV.

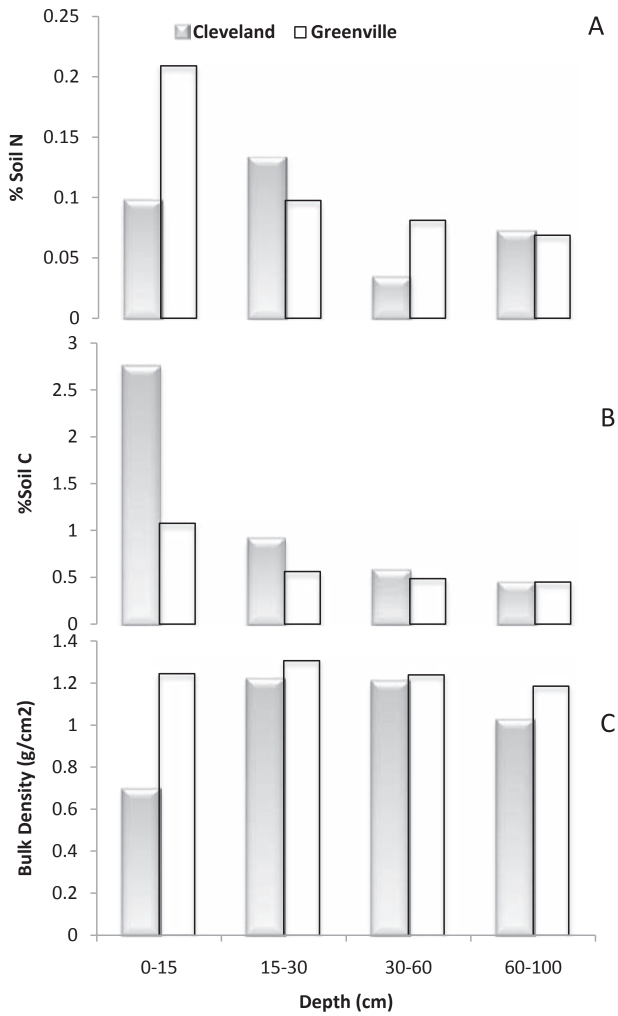

Figure 2—Changes in soil properties with depth: (A) mean amount soil N, (B) mean amount soil C, and (C) bulk density of the soil with depth on two former agricultural sites at the LMAV.

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CARBON STORAGE, SOIL CARBON DIOXIDE EFFLUX AND WATER QUALITY IN THREE WIDTHS OF PIEDMONT STREAMSIDE MANAGEMENT ZONES

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Abstract—Streamside management zones (SMZs) are used to protect water quality. Monitoring carbon pools and fluxes in SMZs may a good indicator of the SMZ's overall function and health. In this project we evaluated some of these pools and fluxes from three different SMZ widths (30.5, 15.3, and 7.6 m) in the Piedmont of Virginia. We quantified carbon storage in the soil (upper 10 cm), litter layer, and plant community, monitored soil carbon dioxide (CO_2) efflux and measured total organic carbon and benthic communities in stream water samples. The narrowest 7.6 m SMZ width did show changes in ecosystem function (litter decrease, soil moisture increase, soil CO_2 efflux increase) which could result in long-term impacts. At this point in time (3 years post harvest), no significant differences were found in the benthic community. The 15.3 m thinning treatment did consistently have the highest total organic carbon (TOC) which may be related to the disturbance from harvesting.

INTRODUCTION

Both agricultural and silvicultural activities may impair water quality due to the increased potential of sediment reaching either the streams or watersheds present near these activities. In recent years, forestry best management practices (BMPs) have been implemented in an attempt to improve or maintain water quality as required by the Federal Water Quality Control Act of 1972 (Aust and Blinn 2004). One of the BMP recommendations that specifically targets the protection of streams and other bodies of water is streamside management zones (SMZs). The Virginia Department of Forestry defines an SMZ as an "an area of reduced management activity on both sides of the banks of perennial and intermittent streams and bodies of open water where extra precaution is used in carrying out forest practices in order to protect bank edges and water quality" (Virginia Department of Forestry 2002). SMZs have many functions including the trapping of both sediments and nutrients; stream bank stabilization, temperature control, and protection of the forest floor (Governo and others 2004). This particular study focuses on the accumulation and cycling of carbon. A complete understanding of both carbon stocks and exchanges between vegetation, soil, and the atmosphere must be obtained in order to have a better understanding of the carbon cycle within terrestrial ecosystems (Cao and Woodward 1998). Knowing how the carbon cycle within SMZs is impacted is important to understanding their long-term effectiveness.

Carbon serves as a building block for most of nature. For this reason, carbon has been studied quite extensively and yet there is still much to be discovered. It is well know that carbon exists in many different forms and therefore in many different pools within the terrestrial ecosystem, including SMZs. Consequently, the presence of carbon drives many of the ecosystem functions within the riparian area and can be used as a determinant of both water quality and SMZ processes. Within the terrestrial ecosystem, carbon moves through the vegetation, soil, and litter layer and escapes back into the atmosphere through autotrophic and heterotrophic respiration (Cao and Woodward 1998). According to Giese and others (2003) riparian areas have high potential to store carbon due to their relatively high rates of productivity and the persistent soil water saturation. Studies have been developed to determine total carbon within an area (Giese and others 2003, Governo and others 2004, Trettin and others 1999) but little research has been conducted to determine how silvicultural management practices may impact the flow of carbon through SMZs.

The benthic macroinvertebrate community tends to be sensitive to any disturbance within the habitat. Due to this, macroinvertebrate sampling is done frequently to determine the health of a stream. Stone and Wallace (1998) found that logging might alter the site by changing the energy of the stream from allochthonous (outside of the system) to autochthonous (within the system). For this reason it is believed that any change in carbon pools would result in a change in the benthic macro invertebrate population. The objective of this project is to determine the influence various SMZ treatments (harvesting intensity; varying widths) have on either the components of the carbon cycle or accumulation of carbon within the stream water. Specifically we will identify the impact these treatments have on aboveground biomass, litter layer, soil carbon (10 cm depth), and total soil CO_2 efflux, examine the influence of these SMZ treatments on environmental drivers of carbon flux (soil moisture and temperature), and determine the effects of these treatments on benthic macro invertebrate populations present within the stream.

MATERIALS AND METHODS

Study Site Description

A field experiment was designed that would allow us to investigate the effects of different SMZ widths and thinning in SMZs upon the riparian carbon dynamics and stream benthic community. This experiment consisted of four SMZ treatments (30.5 m, 15.3 m, 15.3 m with thinning and 7.6 m wide SMZs) with three to six replications across sixteen

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watersheds. Treatment widths are per streamside, and thinning is defined as the removal of approximately 50 percent of the basal area. Not all treatments were installed properly when commercially harvested which resulted in an incomplete block design.

The watersheds consist of first order headwater streams that are ephemeral to intermittent in nature. They are all located on MeadWestvaco property within the Piedmont in Buckingham County, VA in 23 to 25 year old *Pinus taeda* L. (old loblolly pine) plantations (Walker-Easterbrook and others 2003). Overstory vegetation predominantly consists of planted loblolly pine and native hardwoods such as *Acer rubrum* (red maple), *Quercus* spp. (oaks), and *Carya* spp. (hickory). This study was set up as a long-term study with pre-harvest data collected and analyzed in 2002. In 2003 the watersheds were clearcut and in 2004 post-harvest sampling commenced. In addition to the carbon and benthic study, erosion studies are also being conducted.

Field and Lab Techniques

A complete inventory was performed on the following strata: over story, shrubs, and groundcover. The center of the sampling plots was positioned in the middle of one side of the SMZ. For the 7.6 m-wide treatment, the center of the plot was placed in the stream to ensure that the plot did not extend outside of the SMZ. Overstory was defined as any vegetation with a diameter > 9.1 cm (3.6 inches) at 1.3 m above ground diameter breast height (d.b.h.). An 8.01 m radius circular plot (1/20-acre) was established and all vegetation meeting these requirements was measured for height and d.b.h. by species. Shrubs were defined as any vegetation with a diameter < 9.1cm at d.b.h. For shrubs, a circular plot with a 2.5 m radius (1/200 acre) was established along the same location within the transect and all species, number, and heights were recorded. A 1/1000 acre (1.1 m radius) ground cover plot was established and all vegetation within the plot was clipped to the ground line and transported to the lab for dry weight determination. The data collected in the field for both the over story and shrub strata was used in conjunction with existing biomass equations to estimate aboveground biomass within each treatment (Clark and others 1986, Hauser 1992). Carbon was assumed to account for about 50 percent of tree dry weight (Birdsey 1992). Consequently, biomass estimates were converted to carbon by multiplying by 50 percent. The groundcover samples were brought back to the lab and dried at 85 ˚C in an oven and then weighed.

In addition to biomass, the litter layer was sampled twice during the year once in late summer (September 2005) and again following leaf off in the winter (January 2006) at three locations (creek side, middle of SMZ and upper edge of SMZ). The two seasonal sub samples and locations in the SMZ were averaged for analysis. Litter sub samples were taken at the exact same time and location as a measure of total CO_2 efflux. A soil CO_2 efflux measurement was taken and the area (506.5 cm^2) underneath the efflux chamber was removed. Both the litter layer and the entire O horizon were collected. Samples were brought back to the lab and dried at 85 ºC in an oven to a constant weight and then weighed. These dry samples were then placed in muffle furnace at 380 ºC for 24 hours to correct for mineral soil contamination. Litter weight was calculated as oven dried weight minus ash weight obtained from the muffle furnace (Wiseman and Seiler 2004).

In November 2005, ten pushtube soil samples were taken at each of the three sub sample locations (creek side, middle and upper edge) along each transect. These 10 samples were taken along a 10 foot linear transect running perpendicular to the original sub sample location. Pushtube samples were taken to a depth of 10 cm. These samples were mixed together and a single composite sample was brought back to the lab for further analyses. In addition to pushtube samples, an undisturbed bulk density soil sample was taken to the depth of 10 cm using a double-cylinder bulk density corer. Bulk density cores were brought back to the lab and dried at 105 ºC for 24 hours and weighed in order to determine bulk density. These samples were subsequently ground using a mortar and pestle and passed through a 0.64 cm mesh to separate the coarse fragments (Chen and Xu 2004). These coarse fragments were then weighed in order to determine percent coarse fragment content. The separated soil was analyzed for percent carbon content using an Elmentar varioMax CNS analyzer (Elementar American Inc., Mt. Laurel, NJ).

Beginning in May 2005 and continuing through January 2006, total soil CO_2 efflux, soil temperature, and soil moisture was measured on five different dates in an attempt to capture seasonal variation. Measurements were taken along the same transects and locations as with the litter measurements. The order these three locations were measured within the transect was randomized each time. A 15 cm Digi-Sense® thermocouple thermometer (Cole-Parmer, Vernon Hills, IL) was utilized to determine soil temperature to a depth of 15 cm. Soil moisture was measured using a Trase® 6050X1 time domain reflectometer (Soil Moisture Equipment Corp., Golena, CA) to a depth of 13 cm. Total soil CO_2 efflux was measured using a Li-Cor 6200 infrared gas analyzer (Li-Cor Inc., Lincoln, Nebraska) with a dynamic closed cuvette chamber system. The system was constructed of PVC pipe walls, Plexiglas top, and a stainless steel edge on the bottom to ensure a tight seal once placed on top of the sampling location. The internal diameter of the chamber was 25.5 cm and the height was 13.5 cm creating a total volume of 6744 cm^3. Plastic tubing (0.32 cm diameter) was used to attach the cuvette chamber to the infrared gas analyzer. Air enters the cuvette chamber through an input hose on the side of the chamber. This air is then diffused through the chamber via a perforated hose that runs along the interior wall of the chamber. Air then leaves the system through a hose that is located at the top of the chamber through the Plexiglas top (Selig 2003). Before each sampling date, the system was calibrated in the lab by running a known CO_2 concentration through the system. Care was taken to be sure no living plant material was in the chamber and that CO_2 concentrations were at or near ambient levels near the ground line. After CO_2 concentrations were found to be steadily rising in the chamber, a measurement period of 30 seconds was used to estimate total soil CO_2 efflux.

Water samples were taken seasonally in order to estimate total organic carbon (TOC). Water grab samples were taken from a downstream portion of the stream to ensure the presence of water. Three 25 ml bottles were filled by placing them in the stream with the open end facing upstream to capture flowing water. These bottles were then placed on ice and brought back to the lab where they were placed in the freezer until further analysis could be performed. The water samples were then analyzed for TOC. The samples were analyzed using persulfate-ultraviolet oxidation. In order to remove any inorganic carbonates, the samples were purged prior to analysis using oxygen. The instrument used was a Seiver DC80 TOC analyzer with an autosampler.

Samples were also taken from the streams to determine the benthic macroinvertebrate populations. This sampling occurred in January 2006 two to three days after a rain to ensure the most amount of water present for sampling purposes. A D-frame macro invertebrate sampling net was utilized along a 50 m stretch of stream. Along this 50 m stretch a subsample was collected every 2 m. The benthic samples were then washed in a 500µm mesh bottom wash bucket and stored in 90 percent ethyl alcohol. The macroinvertebrate samples were sorted and separated from all gravel pieces and woody debris pieces that may have been collected. These samples were then stored in 95 percent ethanol (EtOH) and later identified to family by Stephen Hiner, an aquatic entomologist technician at Virginia Polytechnic Institute and State University. The results of these sample counts were then applied to various macroinvertebrate metrics.

Statistical Analyses
Data were analyzed as an Incomplete Block Design using an analysis of variance (ANOVA) to determine if differences between treatments existed (SAS v 9.1, Cary, NC). Differences in means were determined by using Tukey's Studentized range test (HSD) at the α= 0.1 significance level. The three different biomass strata were analyzed separately. For data that was not normally distributed a log transformation was performed and the back transformed means are reported. For the respiration data, the analysis was performed as a repeated measure with both soil moisture and soil temperature as covariates. In addition to a repeated measure analysis, each respiration measurement date was analyzed separately. A means separation analysis was performed on litter layer, soil moisture, and soil temperature (Number Cruncher Statistical Systems, Kaysville, UT) to detect significant differences between SMZ treatments and subplot location in these three independent variables.

RESULTS AND DISCUSSION
No differences in total standing biomass carbon were found between SMZ treatments (fig. 1, p=0.3061). The 15.3 m thinned treatment did have the least standing carbon. No differences in total groundcover carbon nor shrub carbon were found between the SMZ treatment (fig. 2, p=0.4304 for groundcover, p=0.2587 for shrubs). The 15.3 m thinned treatment did have the least groundcover and shrub carbon,

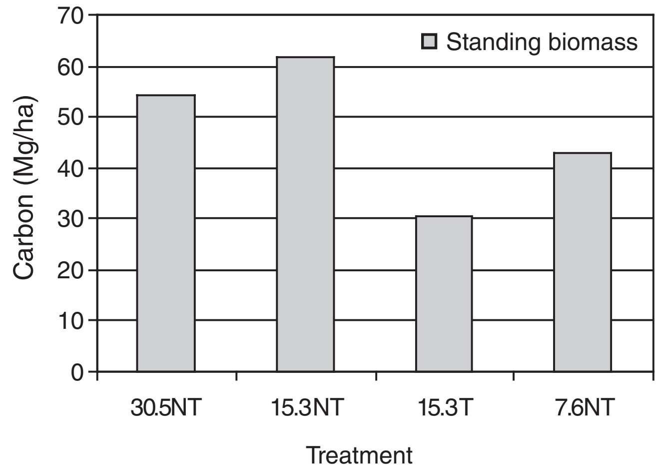

Figure 1—Aboveground standing biomass as influenced by streamside management treatment [numbers (e.g., 30.5) are SMZ width in meters, NT=no thinning, T=thinning] on the Piedmont of Virginia.

while the 7.6 m no thin treatment had the most groundcover and shrub carbon. A study by Peterson and others (1997) demonstrated that during the six years following a thinning treatment regime, the trees responded with both increased crown dimensions and bole diameter increases. Our sampling occurred only two years following the harvest, therefore residual trees had not yet reoccupied the site fully.

The average litter layer in the 7.6 m SMZ was found to be significantly less than the 15.3 m treatments (fig. 3). As would be expected given the short time treatments have been installed, soil carbon showed no significant difference due to the SMZ treatment (p=0.2361) or subplot location (p=0.4775)

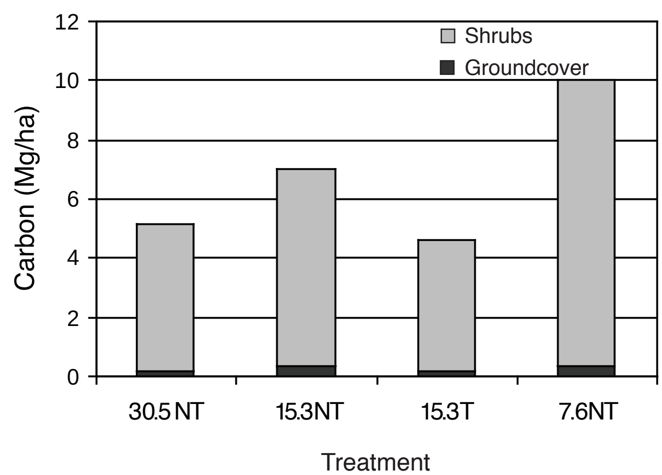

Figure 2—Aboveground groundcover and shrub biomass carbon as influenced by streamside management treatment [numbers (e.g., 30.5) are SMZ width in meters, NT=no thinning, T=thinning] on the Piedmont of Virginia.

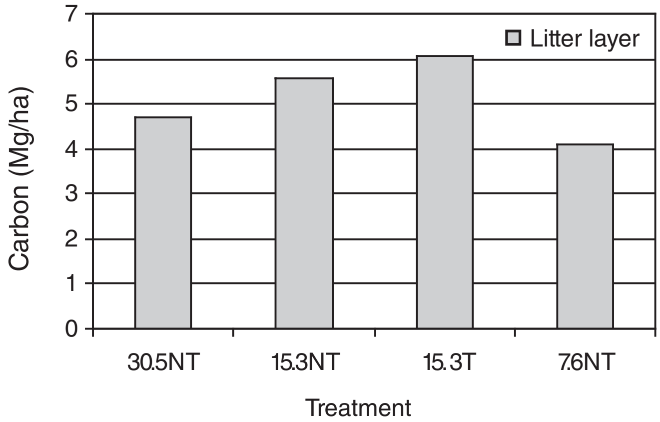

Figure 3—Litter layer carbon as influenced by streamside management treatment [numbers (e.g., 30.5) are SMZ width in meters, NT=no thinning, T=thinning] on the Piedmont of Virginia.

effect. The results did show a significant interaction between SMZ treatment and subplot location (p=0.0628). This was due to the 15.3 m thin treatment showing a large soil carbon concentration at the creek side subplot location. This high value appears to be due to prior high soil organic matter concentrations at a few locations.

Although the 7.6 m SMZ width did show a slight increase in temperature during the fall months (fig. 4A), soil temperature was not significantly impacted by the SMZ treatments (table 1). However, soil moisture did show a consistent and significant effect with the 7.6 m treatment having consistently the highest soil moisture (table 1 and fig. 4B). Soil CO_2 efflux did not demonstrate a large change due to SMZ treatment but the 7.6 m treatment generally had the greatest rates over the time of this study (table 1 and fig. 5). This is perhaps due to the effect of the higher soil moisture and the slightly higher temperature (Lloyd and Taylor 1994, Davidson and others 1998). A study conducted on similar sites on the Piedmont of Virginia by Wiseman and Seiler (2004) indicated both soil temperature and soil moisture as two of the main driving factors influencing soil CO_2 efflux.

Water sample collection was attempted at all 16 watersheds on 5 dates. Grab samples were never collected from one of the watersheds due to the absence of water. In addition, one other watershed was only collected from once and this collection occurred after remnants of a hurricane passed through the area. This one collection during high flow instead of base flow, resulted in a highly significant date effect (p=<0.0001). Thinning can increase the amount of large wood debris that is present within the riparian area therefore increasing the potential for introduction of carbon into the water system. The additional large woody debris can also form organic debris dams which assist in the control of exportation of particulate matter downstream (Bilby 1981). Samples that were taken from the 30.5 m no thin treatment had lower TOC than the other treatments during the hurricane season and consequently during high

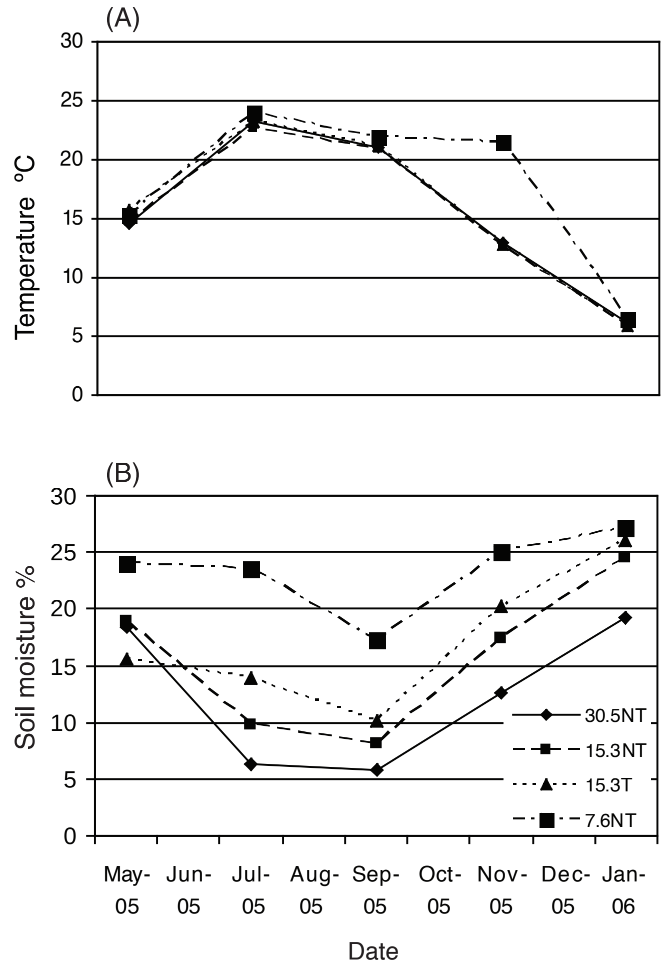

Figure 4—Seasonal trends in soil temperature (A) and soil moisture (B) as influenced by streamside management treatment [numbers (e.g., 30.5) are SMZ width in meters, NT=no thinning, T=thinning] on the Piedmont of Virginia.

Table 1—Seasonal means for soil temperature, soil moisture and soil CO_2 efflux as influenced by the streamside management zone treatments

Streamside management treatment	soil temperature (°C)	soil moisture (%)	soil CO_2 efflux (uMol/m^2 s)
30.5 m width	15.6 a	12.5 a	3.4 a
15.3 m width	15.4 a	15.8 a	4.2 ab
15.3 m width, thinned	15.8 a	17.2 ab	4.0 ab
7.6 m width	16.0 a	23.4 b	5.0 b

Means in a column followed by the same letter do not differ significantly (p=0.05).

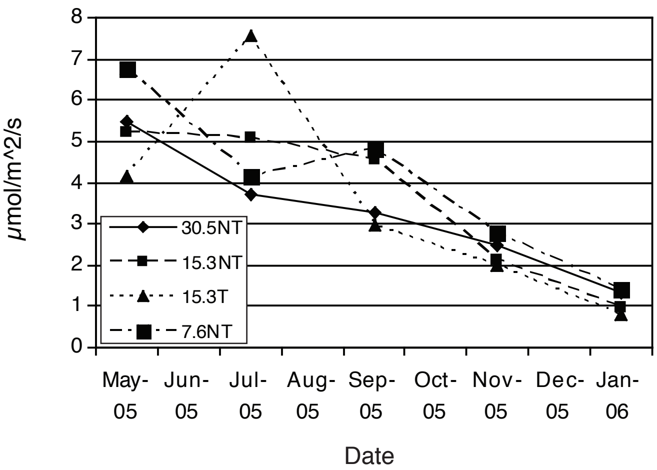

Figure 5—Seasonal trends in soil CO_2 efflux as influenced by streamside management treatment [numbers (e.g., 30.5) are SMZ width in meters, NT=no thinning, T=thinning] on the Piedmont of Virginia.

flow suggesting that the width of the SMZ may reduce the potential of carbon from entering the stream during storm events. No significance was detected among treatments ($p=0.8396$) and interaction between treatment and date ($p=0.9876$).

Only 13 of the 16 streams were sampled for benthics due to the absence of water. A total of 12 macro invertebrate orders and 31 families were identified within the 13 streams that were sampled. One genus that was found is rare, *Anisocentropus*. In addition, a few families were found in only one stream. Although no significant differences were found for any of the analysis for treatment differences, the 15.3 m no thin treatment had the better index value in 7 of the 10 tests performed. The same treatment also yielded the highest TOC present in the water samples. Studies have shown that the introduction of LWD to streams and consequently the habitat improvement, potentially shifting the benthic populations (Lemly and Hilderbrand 2000).

CONLCLUSION

The 7.6 m SMZ width did indicate some changes in ecosystem function (litter decrease, soil moisture increase, soil CO_2 efflux increase). With time, these initial changes we measured could result in changes in soil carbon concentration and water quality changes. Based on these measured variables a 15.3 m SMZ even with thinning appears adequate to prevent changes in water quality.

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EFFECTS OF NUTRIENT AND ORGANIC MATTER MANIPULATION ON CARBON POOLS AND FLUXES IN A YOUNG LOBLOLLY PINE VARIETAL STAND ON THE LOWER COASTAL PLAIN OF SOUTH CAROLINA

Michael Tyree, John Seiler, and Chris Maier[1]

Abstract—Manipulation of site organic matter and nutrients, in addition to planting of superior genotypes will likely influence carbon fluxes from intensively managed forests. The objective of this research is to monitor total soil carbon dioxide (CO_2) efflux (F_S), microbial respiration (R_H), and leaf gas exchange (P_N) in a two-year-old loblolly pine (*Pinus taeda* L.) stand located on the Lower Coastal Plain of South Carolina, which has undergone logging residue (LR) and nutrient additions. Short-term results showed a 17 percent decrease in stem volume with the addition of LR, and showed only modest improvement with the addition of nitrogen (N) and phosphorous (P). However, fertilizer alone increased stem volume by 40 percent and increased P_N in needles produced in 2006. LR and fertilization had no consistent effect on F_S, but showed a tendency to increase and decrease R_H, respectively. Most notably, varieties showed a significant and sustained difference in F_S, which was partially explained by increased R_H and fine-root length. These early results suggest that clonal varieties respond differently to site manipulations and nutrient additions and some of these measured responses have implications for long-term C storage.

INTRODUCTION

Southern pines in the southeastern United States are some of the most intensively managed and highly productive forested ecosystems in the world (Allen and others 2005). Currently, southern pine plantations occupy more than 13 million ha and are forecast to increase 67 percent to 22 million ha by the year 2040 (Wear and Greis 2002). Increasing future demands on forest products produced from these forests as well as growing concern over rising atmospheric CO_2 levels has begged the question, how can we manage these forests to maximize both forest production and carbon sequestration?

A treatment which has long been used in agriculture and mine reclamation is the addition of organic residue to the soil. A tremendous volume of logging residue (LR), up to 5-50 Mg/ha (Allen and others 2006) is generated during a typical harvesting operation of a southern pine stand. This slash represents huge stores of organic carbon, which left exposed to the air will largely oxidize being released back into the atmosphere as carbon dioxide, thereby robbing the site of any potential benefits that may be gained by retaining organic carbon and nutrients. More recently forest managers have begun to spread this logging debris back onto the site in an attempt to keep those nutrients on site. Further, an idea has been proposed to incorporate this LR back to the soil. Not only would this provide nutrients to successive stands, but may additionally increase soil carbon sequestration as it is likely some fraction will remain as recalcitrant soil carbon (C).

Manipulation of site nutrients could lead to large increases in forest productivity as well as help to overcome any immobilization caused by organic additions. Over the last couple decades we have greatly increased our understanding of how to manipulate site nutrients to increase forest productivity. In fact, as of 2005, approximately one half million ha of planted pines have undergone some type of nutrient amendments (Fox and others 2007). As Allen and others (1990, 2005) stated, this is only a fraction of the forested stands that have the potential to respond to fertilization.

As the use of chemical fertilizer increases in intensively managed pine forests it becomes necessary to understand how net ecosystem productivity (NEP) will be impacted by such additions. For instance, it is well established that fertilization will increase above ground productivity due to increased leaf area. Additionally, there is growing evidence that fertilization, specifically nitrogen fertilization, suppresses the rate of decomposition either through reduced microbial activity (Gough and Seiler 2004, Tyree 2005), decreased biomass (Blazier and others 2005, Lee and Jose 2003), changes in microbial populations (Frey and others 2004, Wallenstein and others 2006), or some combination. Either of these outcomes could lead to increased NEP.

Advances in breeding and genetically modified plants to produce superior genotypes have opened an exciting area of research that shows potential for increasing productivity of southern pine forests. Allen and others (2005) estimated volume gains from 10 to 30 percent in superior clones over standard planting stock. Improvements in carbon allocation, photosynthetic capacity, drought and pest tolerance, and resource use efficiency are a few ways in which carbon capture (yield) can be increased.

Changes made to site organic matter and nutrients can have diverse and long lasting impacts on site carbon pools and fluxes, and ultimately, on the carbon balance of a site. NEP is the difference between two competing processes. 1. The capture of inorganic C in the form of CO_2 from the atmosphere and its fixation into biomass (gross primary productivity, GPP) minus growth and maintenance respiration (net primary productivity, NPP). 2. The release of CO_2 back into the atmosphere as a result of decomposition and oxidation of soil organic C by soil microbes (heterotrophic respiration, R_H). Active management of site nutrients and LR may dramatically impact one or both of these processes making our understanding of these changes crucial to our ability to manage, control, and predict changes to NEP on intensively managed pine forests. This research utilizes a two-year-old loblolly pine (*Pinus taeda* L.) varietal plantation

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located on the Lower Coastal Plain of South Carolina. The objectives are to determine how manipulation of site C and nutrients impact aboveground stem biomass, net photosynthesis, total CO_2 efflux, and microbial respiration between two superior loblolly pine varieties one year after treatment initiation.

MATERIAL AND METHODS

Site Description

The site is located in Berkeley County, SC. Elevation is 24 m above mean sea level. Average yearly temperature is 17.8 °C with average daily maximum of 24.1 °C and an average daily minimum of 11.6 °C. Highest daily average temperature is 26.7 °C which occurs during July, and a low of 8.2 °C, which occurs in January. Average yearly precipitation is 120 cm with the highest rainfall of 18 cm in July and a low of 5 cm occurring in November. The dominant soil series on site is Ocilla (loamy, siliceous, semiactive, thermic Aquic Arenic Paleudults). The previous 21-year-old loblolly pine stand was harvested in May 2004 and sheared in June 2004. Logging residue was spread by hand in June and July 2004. Site preparation (bedding) took place in October 2004, and the current loblolly pine seedlings were planted in January and February of 2005.

Experimental Design

This study is designed as a split-plot randomized complete block design replicated three times with the whole-plot treatments arranged in a full 2 by 2 factorial measured repeatedly. Each 0.18 ha plot was planted with 243 container grown varietal loblolly pine (*Pinus taeda* L.) seedlings in nine rows at 4.3 m between row centers. The logging residue (LR) whole-plot treatment consists of two levels of LR incorporation. No LR incorporated and LR incorporated into the mineral soil at an equivalent rate of 25 Mg/ha ovendry weight (o.d.) concentrated onto the beds. Both LR treatments retained original forest floor of approximately 25 Mg/ha o.d. on the surface. The second whole-plot treatment is two loblolly pine varieties. Variety 93 is considered a high leaf efficiency variety with high stem volume produced per unit leaf area. Variety 32 has a lower leaf efficiency and greater overall leaf area. Each plot is split into two 0.0013 ha measurement plots consisting of six seedlings, which are located at opposite ends of the whole-plot, and serve as the experimental unit (EU). Each EU received one of two fertilizer treatments. No nutrient additions or the addition of 209 kg-N and 116 kg-P/ha in the form of diammonium phosphate and ammonium nitrate. Fertilizer was applied on two separate dates. Roughly 1/3 was applied on April 6, 2006 and the remainder applied on May 8, 2006.

Measurements

Aboveground measurements—Aboveground height and ground-level diameter were measured nine times over the 2006 growing season and used to calculate above ground stem volume (diameter squared x height). Net photosynthesis (P_N) was measured 14 times between January 2006 and 2007 on a single detached fascicle from the upper third, south facing side of the tree between 1100 and 1600 hours. Gas exchange measurements were taken using an open-flow, infrared gas analyzer equipped with a 2 by 3 cm cuvette and a blue-red LED light source (LiCor 6400, Lincoln, Nebraska). Measurements were taken on two seedlings per EU with the following chamber conditions: 1600 µmol/m²/sec PPFD, 370 µmol/mol reference CO_2 concentration, ambient temperature and humidity, and flow rate at 300 µmol/sec. Following P_N needles were immediately removed and fascicle diameter measured to the nearest 0.01 mm using digital calipers. P_N was expressed per unit leaf area based on the following equation (Ginn and others 1991):

$$LA = (n \times l \times d) + (\pi \times d \times l) \tag{1}$$

where *l* is the length of the needle in the chamber (3 cm), *d* is the diameter of the fascicle measured just above the sheath, and *n* the number of needles in the fascicle.

Belowground measurements—Total soil CO_2 efflux (F_S) was measured at the soil surface near and away from the second tree in each plot using a Li-Cor 6200 infrared gas analyzer (Li-Cor Inc., Lincoln, Nebraska) with a closed cuvette chamber constructed from a PVC pipe for walls, and a Plexiglas top (25.5 cm internal diameter, height at center 13.5 cm). The bottom of the chamber was fitted with a stainless steel edge that was pressed approximately 1 cm into the soil to create a complete seal giving a total system volume of 6300 cm³ (Selig 2003, Tyree 2005). The machine was calibrated before each sampling date by running a known CO_2 concentration and making necessary adjustments to the IRGA. Between blocks the system was zeroed to account for any drift due to changes in temperature. Respiration measurements were made in the same sequential blocking order at approximately the same time of day for each sampling date. The CO_2 concentration in the cuvette chamber was lowered to ambient atmospheric CO_2 concentration then placed on the soil surface on a spot free of living, photosynthesizing vegetation. After efflux rates began to steadily rise, CO_2 evolution was measured over a 30 second period and respiration rates calculated on a per unit land area.

An index of microbial respiration (R_H) was measured using the LiCor 6250 infrared gas analyzer (Li-Cor Inc., Lincoln, Nebraska) with a 0.25 L cuvette chamber, with a total system volume of 429 cm³. Four to six cores were taken systematically near and away from trees throughout the plot to a depth of 30 cm (or to depth of water table) with a 2.5 cm diameter pushtube and mixed into a single composite sample. Roots were carefully removed from the soil by hand, and the soil placed into an aluminum weigh boat (10 cm by 2 cm), which was placed into the 0.25 L cuvette chamber (Gough and Seiler 2004, Tyree 2005). Once the CO_2 concentration began to steadily rise (typically within one minute) R_H was measured over a 30 second period. Soil was brought back to the lab, oven-dried for 48 hours at 105 ºC, and weighed gravimetrically to the nearest 0.01g. R_H was calculated and expressed on a per soil mass basis (µmol/kg-soil/min). This was repeated twice in each measurement plot and sub-samples averaged together to arrive at a single R_H value.

Data Analysis
Significant (*P* = 0.05) treatment (i.e., varietal, LR, fertilization, and interactions) differences were determined by analysis of variance with repeated measures (ANOVARM) using the MIXED procedure in SAS version 9 (SAS. 1999). Covariance structures were selected using Schwarz's Bayesian goodness (BIC) of fit criteria. When necessary individual sampling dates were analyzed using the GLM procedure. Residuals and the normality curves were plotted for all analyses to confirm that data met assumptions of equal variance and normality for all parameters measured. All values are expressed as untransformed averages and standard errors.

RESULTS AND DISCUSSION

Aboveground Measurements
We observed a highly significant (*P* <.0001) LR by fertilizer by time interaction in aboveground stem volume (fig. 1a). By the end of the second year the addition of LR decreased above ground stem volume by approximately 17 percent relative to control plots. Adding fertilizer resulted in a slight, but non-significant, increase in stem volume when LR was present. We hypothesize the amount of fertilizer added was not enough to overcome any immobilization caused by the addition of high C:N (about 700) LR, but this has yet to be tested. The addition of fertilizer alone resulted in a 40 percent increase in stem volume relative to control plots, which is similar to other first year fertilizer responses in young loblolly pine (Gough and others 2004b, King 2005).

Both varieties showed a decrease in stem volume with the addition of LR, but variety 93 was less inhibited than variety 32 (fig. 1b). Interestingly, both clones responded similarly to fertilizer additions showing no significant fertilizer by variety (*P* = 0.65), or fertilizer by variety by time (*P* = 0.99) interactions. This indicates that variety 93 may acquire or utilize N, P, or both more efficiently than Variety 32 when nutrients are limiting, but under conditions where N and P are plentiful varieties 32 shows a slight increase in stem volume. In support of this theory, Li and others (1991) showed that components (uptake and utilization efficiencies) of nitrogen use efficiency (NUE) (stem biomass produced per unit of N applied) in *P. taeda* seedlings were moderately to highly dependent on genotype.

We found no significant difference ($P > 0.1$) in P_N between LR treatments or varieties. Over all sampling dates there was no fertilizer effect between treatments; however, on a number of dates fertilized plots had significantly greater P_N rates than controls (fig. 2). Slicing the data based on year of needle development showed a significant ($P = 0.02$) increase in P_N in fertilized plots for needles produced in 2006. In June and December 2006 there were significant ($P < 0.05$) interactions between fertilizer and variety for P_N. In both instances Variety 93 responding more favorably to fertilization than Variety 32. Similar increases in P_N to fertilization have been shown in loblolly pine (Gough and others 2004b, Samuelson 2000), while others have shown little to no difference (Gough and others 2004a, Maier and others 2002).

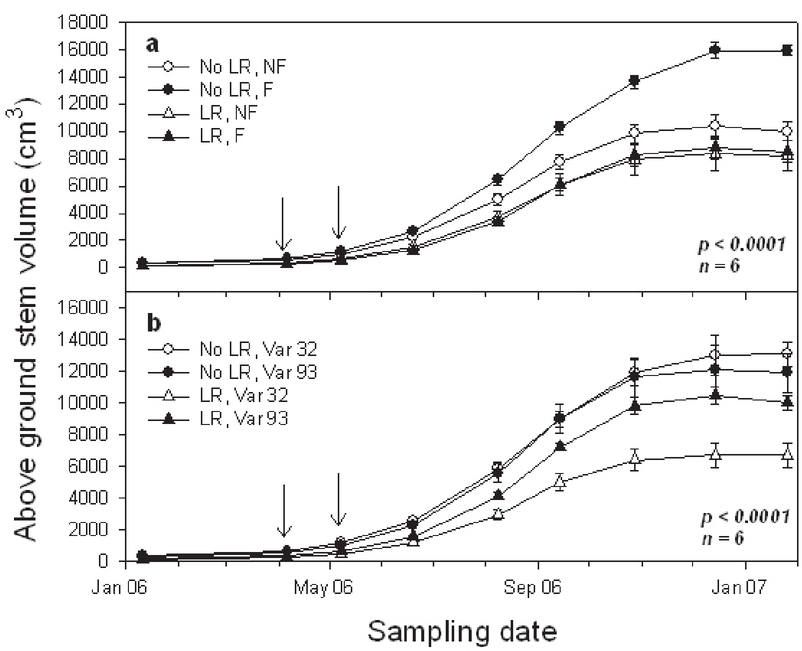

Figure 1—The influence of logging residue (LR) and fertilizer (a), and LR and loblolly pine variety (b) on second year seasonal stem volume (d^2 x ht) in Berkley Co., SC. Arrows indicate time of fertilization and error bars represent ± one standard error from the mean.

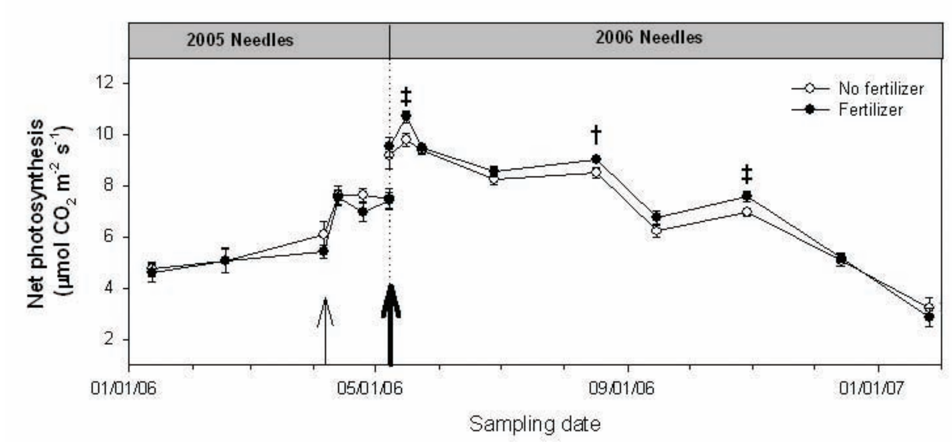

Figure 2—Fertilizer by time interaction for net photosynthesis of most recently elongated, south facing loblolly pine needles measured from January 2006 thru January 2007. Single dagger and double dagger indicate significance at the 0.10 and 0.05 alpha levels, respectively (Error bars show ± 1 standard error from the mean; n = 12). Thin and fat arrows indicate times of light and heavy fertilization, respectively.

Belowground Measurements

In contrast to our hypothesis, the addition of LR resulted in no consistent ($P > 0.1$) effect on F_S. We expected that incorporating a readily available source of organic C into the mineral soil would result in a detectable short-term increase in F_S. One implication is that more of the material incorporated may remain in the soil than previously believed potentially leading to increased soil C. Caution is needed when interpreting these results as no estimate of C loss through leaching has been measured on these plots to date. The addition of LR tended to increase R_H, but overall the effect was not statistically significant ($P > 0.1$). Additionally, fertilization with N and P did not result in a consistent effect on F_S. Work by others suggests that an increase in root respiration accompanied by a decrease in microbial respiration may offset each other resulted in no net difference in F_S (Gough and Seiler 2004, Tyree 2005). We did find a tendency for decreased R_H in plots that received fertilizer which has been shown by others in young loblolly pine plantations (Tyree 2005). This finding was significant on three separate sampling dates, but when all the data were analyzed together the effect was not statistically significant ($P > 0.1$).

Variety 32 had consistently ($P = 0.1$) greater F_S rates than Variety 93 throughout the entire 2006 growing season (fig. 3a). What makes this finding remarkable is that this effect was detectable before full occupation of the site by the trees, which implies planting varieties which differ in their allocation patterns may have substantial short-term and possible long-term impacts on NEP. The observed increase in F_S may be a function of increased below-ground C allocation (root mass, exudates) in Variety 32 relative to Variety 93. Support comes from greater R_H ($P = 0.04$) in Variety 32 plots relative to Variety 93 which may be a result of increased exudates (fig. 3b). Further, preliminary findings from a project collaborator using mini-rhizotrons found greater fine-root length in Variety 32 plots (Seth Pritchard, Dept. of Biology, College of Charleston, personal communication), which could impact both increased root exudation and increased root respiration both which would lead to increased F_S.

CONCLUSION

We monitored a number of C fluxes associated to NEP to determine the impacts site C and nutrient manipulations in a young varietal loblolly pine stand over the second growing season. Early results showed LR and fertilization treatments had dramatic effects on above ground C capture as measured by stem volume. Logging residue decreased above ground stem volume by 17 percent by the end of the second growing season, which was presumably due to N immobilization, but the negative effects of LR were much less apparent in plots planted with Variety 93 relative to Variety 32. N and P fertilization alone increased stem volume by 40 percent, which could be a function of observed increases in P_N, increased C allocation to above ground organs, or both. Notably, N and P fertilization was unable to compensate for the reduction in stem volume when LR was present. In contrast to our hypothesis, the incorporation of LR did not result in increased C loss from the soil as measured by F_S implying that more C remained in the soil. We found consistent differences in F_S between varieties. Variety 93 had significantly lower F_S rates than Variety 32, which was surprising at such a young age. This was further supported by a significant decrease in R_H observed in the Variety 93 plots. These early results indicate that LR incorporation along with careful selection of appropriate planting stock may be a viable method for increasing site C.

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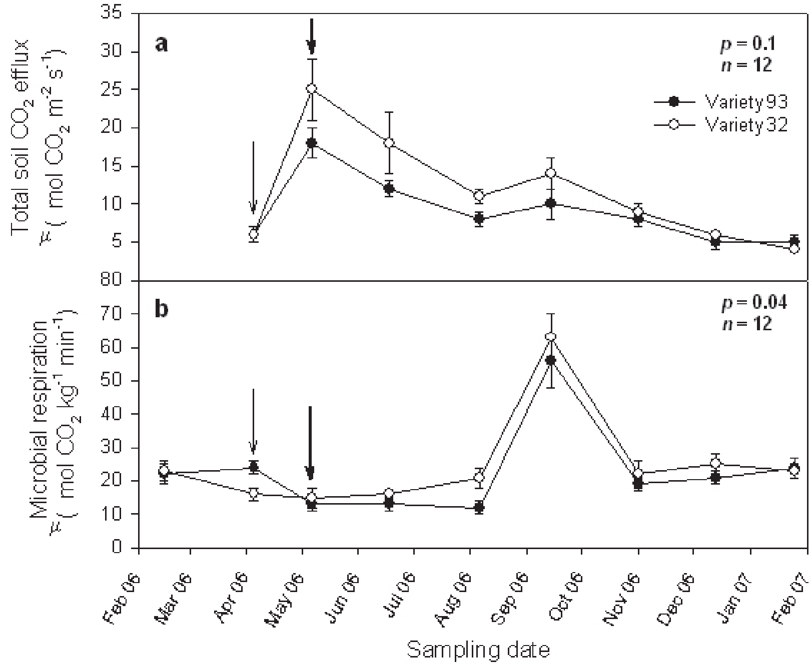

Figure 3—Total soil CO_2 efflux (a) and microbial respiration as influenced by loblolly pine variety (b). Error bars show ± 1 standard error from the mean. Thin and fat arrows indicate times of light and heavy fertilization, respectively.

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Pine Silviculture

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FAMILY BY ENVIRONMENT INTERACTIONS FOR LOBLOLLY AND SLASH PINE PLANTATIONS IN THE SOUTHEASTERN UNITED STATES

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Abstract—Few studies have quantified the combined effects of silvicultural treatments and genetic improvement on unit area production of full-sib family blocks of loblolly and slash pine. We examined genotype (family) by environmental interactions (G x E) through age five years using a factorial experiment consisting of silvicultural treatment intensity, planting density and full-sib families Five years after planting, both loblolly and slash pine demonstrated significant interactions among several factors: G by site ($p < 0.028$ and $p < 0.016$ respectively) and G by silvicultural treatment intensity ($p < 0.055$ and $p < 0.059$ for basal area and standing stem volume). G by silvicultural treatment interactions were positive, large and of the scale-type effe. . Changes in slash pine family rankings between sites were partly explained by a combination of fusiform rust infection [*Cronartium quercum* (Berk.) Miyabe ex Shirai f. sp. *fusiforme*] and wind damage from the 2004 hurricane season.

INTRODUCTION

Considerable gains in the productivity of loblolly (*Pinus taeda* L.) and slash pine (*Pinus elliottii* Englm. Var. *elliottii*) plantations in the Southeastern United States have been achieved over the past 30 years. When a combination of elite genetic materials are combined with site-specific silvicultural treatments, mean annual increments of up to 20 m^3/a/ per year have been documented (Allen and others 2005). However, as resource managers begin to deploy selected full-sib families or clones (Bridgwater and others 2005), there is a greater likelihood that genotype by environmental (G x E) interactions will occur, especially under conditions of increased silvicultural intensity (McKeand and others 2006).

Research studies aimed at quantifying the combined effects of silvicultural treatments and genetic improvement on unit-area production in loblolly and slash pine are rare. Earlier studies indicate that G x E would not be of major consequence for the majority of genotypes being deployed under traditional silvicultural systems (McKeand and others 2006) and tree improvement programs have historically assessed G x E interactions for determining the need for site specific breeding efforts (McKeand and others 1997). While few studies have documented G x E interactions among silvicultural treatments, available evidence suggests that when G x E does occur in these situations, it is caused by relatively few genotypes in the population that were highly sensitive to environmental variation (Zas and others 2004). It appears that G x E may become significant only under extremes in seed source movement and/or site productivity and that relatively few genotypes from the population contribute to this response

The overall objectives of this study were to investigate and quantify the magnitude and nature of G x E in full-sib families of loblolly and slash pine. This was accomplished using a series of replicated factorial experiments and family block plantings established in FL and GA that manipulated gradients in planting density, understory competition, and soil nutrient availability.

METHODS

Study Description

In January of 2000, the Forest Biology Research Cooperative (http://fbrc.ifas.ufl.edu), located at the University of Florida, established a series of installations in southeast GA and northeast FL that were designed to examine interactions of full-sib loblolly and slash pine families with several environmental factors, including study location, nutrient manipulation treatments, and planting density (Roth and others 2002). The topography is nearly flat, with less than a 1 percent slope. Soil series for the four sites were: Sanderson, FL - Leon (sandy, siliceous, thermic Aeric Alaquods); Waverly, GA - Bladen (mixed, semiactive, thermic Typic Albaquults); Perry, FL - Leon (sandy, siliceous, thermic Aeric Alaquods); Waldo, FL - Newnan (sandy, siliceous, hyperthermic Ultic Haplohumods). All study sites share a subtropical and humid climate with long hot wet summers and mild dry winters and long-term (1931–2000) precipitation has averaged 1384 mm/ year (NOAA, 2002).

Experimental Design

The PPINES series is composed of two installations each of loblolly pine and slash pine. Within each installation, the experimental design is a 2 by 2 by 7 (silviculture by planting density by genetic entry) factorial, which is planted in a randomized complete block, split-plot design. Each site has four complete blocks consisting of four silviculture-density whole plots. Silvicultural and planting density treatments are at the whole-plot level and genetic entries are at the sub-plot level

Treatment Descriptions

Each installation was double bedded at 2.75 m spacing and treated in the late summer/early fall of 1999 with pre-plant herbicides with the goal of removing all woody competition and reducing initial levels of herbaceous vegetation. Following planting, competing vegetation was controlled for two years using directed herbicide applications. The intensive plots were fertilized with 660 kg/ha of 10-10-10 plus micronutrients at the time of planting, which was followed by

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annual applications of macro- and micronutrient fertilizers. Contrasting planting densities of 1 334 trees/ha and 2 990 trees/ha were created by varying the spacing within beds. Genetic were represented by first generation full-sib genetic entries: 1) elite families for growth, and 2) a poor grower.

Inventory, Yield and Biomass Estimates

Diameter at breast height (d.b.h.) was measured at age five on all measurement trees. In addition, total height (HT) was measured on a 20 percent sub-sample with the remaining heights predicted from measured d.b.h., using site and treatment specific relationships. Abiotic and biotic tree damage was assessed at the time of measurement. Basal area (BA) was calculated on a per family-plot basis (m^2/ha) which accounts for variation due to mortality. Individual tree stem volume was calculated as the sum of the volume of a cylinder from the base of the tree to 1.37 m in height and the volume of a cone from 1.37 m to the top of the tree. Individual surviving trees per plot were summed and scaled to yield total standing stem volume (VOL; m^3/ha). Aboveground biomass (AGB) equations were developed using a dataset consisting of treatment specific data from this experiment along with supplemental data from several previous regional studies of similar age and treatment history.

Analysis

All analyses were performed using PROC MIXED (Littel and others 1996) in SAS. To test for differences in stand-level attributes among treatments, separate analyses of variance (ANOVA) were performed for loblolly and slash pine using a mixed linear model for data pooled across two sites within each species (equation 1):

$$\begin{aligned} Y_{ijklmn} = {} & \mu + S_i + b(s)_{ij} + C_k + D_l + CD_{kl} + \\ & F_m + CF_{km} + DF_{lm} + CDF_{klm} + SC_{ik} \\ & + SD_{il} + CD_{ikl} + SF_{im} + SCF_{ikm} \\ & + SDF_{ilm} + SCDF_{iklm} + b(s)C_{ijk} \\ & + b(s)D_{ijl} + b(s)CD_{ijkl} + b(s)F_{ijm} \\ & + b(s)CF_{ijkm} + b(s)DF_{ijlm} + b(s) \\ & CDF_{ijklm} + b(s)S_{ij} + b(s)SC_{ijk} + \\ & b(s)SD_{ijl} + b(s)CD_{ijkl} + b(s)SF_{ijm} + \\ & b(s)SCF_{ijkm} + b(s)SDF_{ijlm} + w_{ijklmn} \end{aligned} \quad (1)$$

where Y_{ijklmn} is the response variable (BA, VOL, or AGB) of the *n*th plot of the *m*th family of the *l*th planting density of the *k*th silvicultural intensity of the *j*th block of the *i*th site (i = 1,2; j = 1,2, …, 4; k = 1,2; l = 1,2; m = 1,2,…, 6 for slash and 7 for loblolly pine; and n = 1); μ is the overall mean; S_i is the fixed effect of the *i*th site; $b(s)_{ij}$ is the random interaction effect of the *j*th block within the *i*th site; C_k is the fixed effect of the *k*th silvicultural intensity; D_l is the fixed effect of the *l*th planting density F_m is the fixed effect of the *m*th family and w_{ijklmn} is the random error. Blocks were nested within sites, while the factors of silviculture (C), planting density (D), and genotype (F) were crossed. All terms containing $b(s)_{ij}$ were considered to be random effects in the model and were pooled as appropriate for each variable tested using the procedure described by Bancroft and Han (1983). Where multiple non-planned comparisons were made, a Bonferroni's adjusted significance level was used.

RESULTS

Strong and significant G x E in BA, VOL, and AGB were apparent in this experiment for both species. The strength of the experimental design enabled the detection of two types of unit-area production interactions: genotype by site and genotype by silviculture (tables 1 and 2.). There were no significant three-way interactions involving genotype, site and silviculture. Despite the high statistical power to detect interactions, there was no evidence through age five years for genotype by density interactions of any kind.

Genotype by Site Interactions

At age five there were significant interactions for BA, VOL, and AGB ($p = 0.0271$, $p = 0.0224$, $p = 0.0388$) (table 1). For slash pine, G x E between sites was more significant than those for loblolly by age five ($p = 0.0127$, $p = 0.0157$, $p = 0.0158$) (table 2). The varying performance of families across sites was largely due to scale effects, with certain families performing better or worse than their peers when grown together on contrasting sites (fig. 1).

Genotype by Silviculture Interactions

G x E as influenced by silviculture was significant in loblolly pine for VOL ($p = 0.0019$) (table 1). The significance of the interaction for loblolly pine in BA ($p = 0.0541$) and AGB ($p = 0.0502$) at age five was not as strong as for volume. In contrast, elite families of slash pine were not as responsive to silviculture as loblolly pine and, similarly the performance among slash pine families was more stable when grown under contrasting silvicultural regimes. In slash pine, G x E (as driven by silviculture) was not significant until age five and then only for VOL ($p = 0.0126$); BA was weakly significant at $p = 0.0589$ (table 2).

As with genotype by site interactions, the instability of family performance across contrasting silvicultural treatments was mainly the result of scale effects, where certain families either outperformed or underperformed their peers with increasing intensity of silvicultural treatment. Examination of least squares means for VOL at age five showed that loblolly family L4 was most responsive to increasing silvicultural intensity (75 percent increase), while family L5 was one of the least responsive families (55 percent increase) (fig. 2a). Family L5 also exhibited the least difference in volume growth across contrasting sites (13 percent difference). All other families were intermediate in their response. For slash pine, families S2 and S6 were the most responsive in VOL at age five to increasing intensity of silvicultural treatment intensity (63 percent increase), with all other families exhibiting a lower response (combined 55 percent increase) (fig. 2b).

Effects of Disease and Hurricanes

Plot level, incidence of fusiform rust and wind damage at age five was examined in an attempt to partially explain genotype by site interactions. Despite the fact that all families in the study were selected to have some level of fusiform

Table 1—Summary of statistical significance (prob. >F) and associated degrees of freedom from ANOVA to test loblolly pine basal area, stem volume, and aboveground biomass at age 5 years *

Source of variation	Basal area†			Stem volume‡			Aboveground biomass§		
	Num. df	*Den. df*	*p-value*	*Num. df*	*Den. df*	*p-value*	*Num. df*	*Den. df*	*p-value*
Age 5									
Culture (C)	1	6	**<0.0001**	1	6	**<0.0001**	1	6	**<0.0001**
Density (D)	1	6	**<0.0001**	1	6	**<0.0001**	1	6	**<0.0001**
C x D	1	6	**0.0014**	1	6	**0.0011**	1	142	**<0.0001**
Family (F)	6	136	**<0.0001**	6	136	**<0.0001**	6	142	**<0.0001**
C x F	6	136	0.0541	6	136	**0.0019**	6	142	0.0502
D x F	6	136	0.1022	6	136	0.1149	6	142	0.4576
C x D x F	6	136	0.8249	6	136	0.6683	6	142	0.5154
Site (S)	1	6	**0.0021**	1	6	**0.0028**	1	6	**0.0032**
S x C	1	6	**0.0056**	1	6	**0.0038**	1	6	**0.0005**
S x D	1	6	0.1092	1	6	0.1314	1	6	0.0708
S x C x D	1	6	0.4445	1	6	0.2368	1	142	**0.0007**
S x F	6	136	**0.0271**	6	136	**0.0224**	6	142	**0.0388**
S x C x F	6	136	0.3847	6	136	0.2075	6	142	0.5364
S x D x F	5	136	0.4779	5	136	0.5922	5	142	0.4878
S x C x D x F	5	136	0.6594	5	136	0.5897	5	142	0.4361

Note: * Different models were constructed for each variable within each age with varying random effects in the variance terms; hence the need for different numerator and denominator degrees of freedom in the mixed model. † Basal area is expressed in $m^2 \cdot ha^{-1}$. ‡ Stem volume is expressed in $m^3 \cdot ha^{-1}$ and is calculated as the sum of per tree measurements of the volume of a cylinder to 1.37 m and the volume of a cone from 1.37 m to the top if the tree. § Aboveground biomass is expressed in $Mg \cdot ha^{-1}$. P-values significant at the 95% level of confidence are shown in bold type.

Table 2—Summary of statistical significance (prob. >F) and associated degrees of freedom from ANOVA to test slash pine basal area, stem volume and aboveground biomass at age 5 years *

Source of Variation	Basal area†			Stem volume‡			Aboveground biomass§		
	Num. df	*Den. df*	*p-value*	*Num. df*	*Den. df*	*p-value*	*Num. df*	*Den. df*	*p-value*
Age 5									
Culture (C)	1	6	**<0.0001**	1	6	**<0.0001**	1	6	**<0.0001**
Density (D)	1	12	**<0.0001**	1	12	**<0.0001**	1	12	**<0.0001**
C x D	1	12	**0.0007**	1	12	**0.0002**	1	12	**0.0037**
Family (F)	5	116	**<0.0001**	5	116	**<0.0001**	5	116	**<0.0001**
C x F	5	116	0.0589	5	116	**0.0126**	5	116	0.4432
D x F	5	116	0.2837	5	116	0.1763	5	116	0.1259
C x D x F	5	116	0.4665	5	116	0.5684	5	116	0.7740
Site (S)	1	6	**0.0024**	1	6	**0.0037**	1	6	0.0937
S x C	1	6	0.1441	1	6	0.1880	1	6	0.1037
S x D	1	12	**0.0439**	1	12	**0.0197**	1	12	**0.0369**
S x C x D	1	12	0.2945	1	12	0.2869	1	12	0.3651
S x F	5	116	**0.0127**	5	116	**0.0157**	5	116	**0.0158**
S x C x F	5	116	0.0510	5	116	0.0790	5	116	0.2363
S x D x F	5	116	0.7333	5	116	0.5427	5	116	0.4500
S x C x D x F	5	116	0.9229	5	116	0.8777	5	116	0.9953

Note: * Different models were constructed for each variable within each age with varying random effects in the variance terms; hence the need for different numerator and denominator degrees of freedom in the mixed model. † Basal area is expressed in m2·ha-1. ‡ Stem volume is expressed in m3·ha-1 and is calculated as the sum of per tree measurements of the volume of a cylinder to 1.37 m and the volume of a cone from 1.37 m to the top if the tree. § Aboveground biomass is expressed in Mg·ha-1. P-values significant at the 95% level of confidence are shown in bold type.

rust resistance, there were significant rank changes among slash pine families in fusiform occurrence between sites at age five (p = 0.0189). Similar results have been previously documented in slash pine (Schmidt and Allen 1998). Of the six slash pine families in the experiment, three (S4, S5, and S6) demonstrated a GxE in fusiform rust incidence, with the Waldo, FL location having the highest incidence (fig. 3a). The other three families had a similar but low overall incidence of fusiform rust between sites. Loblolly pine families generally had low incidence of fusiform rust and no significant interactions were found.

In the summer of 2004, two hurricanes, Frances and Jeanne, passed in close proximity to the Waldo, FL site. Damage from these storms was minimal at the Perry, FL site and barely evident at either of the two loblolly sites. There was significant G x E for wind damage in slash pine between sites (p < 0.0001) (fig. 3b). Trees at the two slash pine sites may have toppled due to indirect effects of weak root systems, combined with a relatively large leaf area, or stems may have broken due to fusiform rust galls located on tree stems.

DISCUSSION

This experiment provided the opportunity to quantify the combined effects of silvicultural treatments and genetic improvement on unit-area production in full-sib loblolly and slash pine families. The G x E observed in this study occurred at the two-way level: genotype by site and genotype by silviculture. Genotype by density interactions were not significant. The variety of interactions evident in this study was not surprising given the range of contrasting elite genotypes, silvicultural treatments and study sites

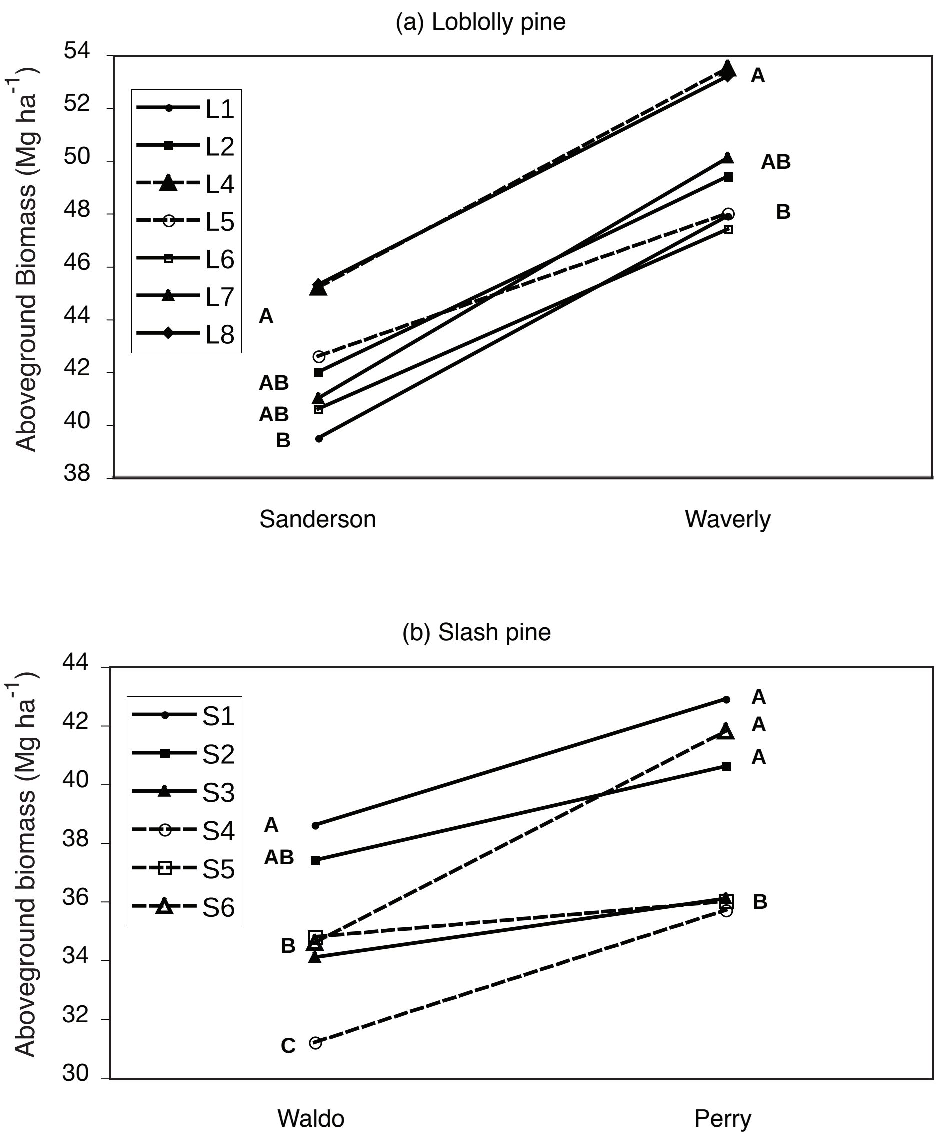

Figure 1—Standing crop biomass (metric tons per hectare) at age five demonstrating a genotype x location interaction for (a) loblolly pine (p=0.0388) and (b) slash pine (p=0.0158). Data points within sites with the same letter are not significantly different at the 90% level of confidence using Bonferroni's Least Significant Difference (LSD).

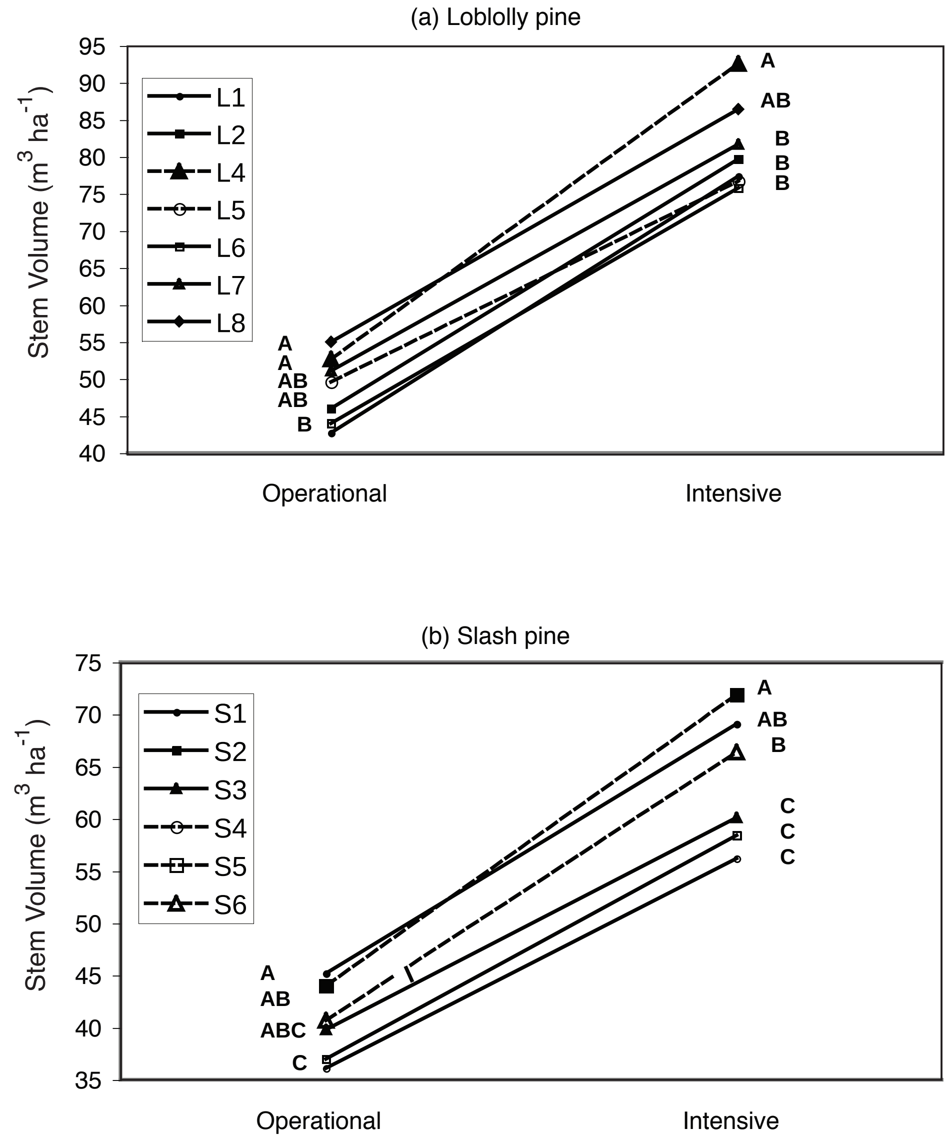

Figure 2—Standing volume (m3·ha-1) at age five demonstrating a genotype x silviculture interaction for (a) loblolly pine (p=0.0019) and (b) slash pine (p=0.0126). Data points within species and cultures having the same letter are not significantly different at the 90% level of confidence using Bonferroni's Least Significant Difference (LSD).

established. When combined with the high statistical power associated with a complex experimental design, we had the ability to detect significant differences in the responses of the elite genotypes across soils, climates and silvicultural treatments that had not previously been observed for plantations of loblolly and slash pine.

Genotype by Silviculture

McKeand and others (2006) suggest that GxE issues in Southern forestry will not become important unless silviculture or propagule type changes significantly from those currently in use. Therefore, it was somewhat surprising that the genotype by site interactions were more significant and consistent than the genotype by silviculture interactions, especially given the extremes in silvicultural intensity. However, the magnitude of increase in productivity with increasing silviculture likely overpowered the statistical significance of this interaction as certain families tended to show greater response than others. One example was loblolly family L4 which is widely deployed in the Southeastern United States and its plasticity with regard to intensive management demonstrates responsiveness considerably greater than its peers. While not of the same magnitude, the same is true for select families of slash pine in this experiment (S2 and S6). This effect of similar relative differences in yield, yet larger absolute differences with increasing silvicultural intensity have been previously demonstrated in loblolly pine (McKeand and others 1997a). It follows that this variation in GxE between sites and silvicultural treatments could potentially be exploited if the relatively few 'responding' genotypes are identified and deployed on the proper sites in combination with site-specific silvicultural treatments.

Genotype by Site

The strongly significant genotype by site interaction, even after accounting for the extremes in silvicultural treatments, is an indication that variation in soils, climate, edaphic variables, and pests (even across relatively short distances) are important regardless of the level of silvicultural intensity. Soil conditions, such as the ability to supply moisture and nutrients, may be partly responsible for the GxE observed in this experiment, as has been suggested by other researchers (Fox 2000). Certain soils with high clay content, such as the Ultisols at Waverly, GA, have a relatively high water holding capacity and when combined with favorable nutrient availability, could potentially supply water and nutrients for a longer duration than the sandy Spodosols at Sanderson, FL. Growth response to nutrition has been shown to vary by family, especially for loblolly pine (Li and others1991, Samuelson 2000). There is also evidence that carbon allocation to above- and belowground tissues is sensitive to soil fertility and varies with provenance and family (Crawford and others 1991, Wu and others 2004). For example, Samuelson (2000) found variation among loblolly pine families in fine root production under low N treatments, but not under high N levels. Examination of foliar nutrition at age five on the current experiment was not able to explain the G x E observed in production at age five (unpublished data).

Genetic variability within a population allows for the potential to buffer against the effects of disease and weather, and is an important aspect of family stability, particularly where there

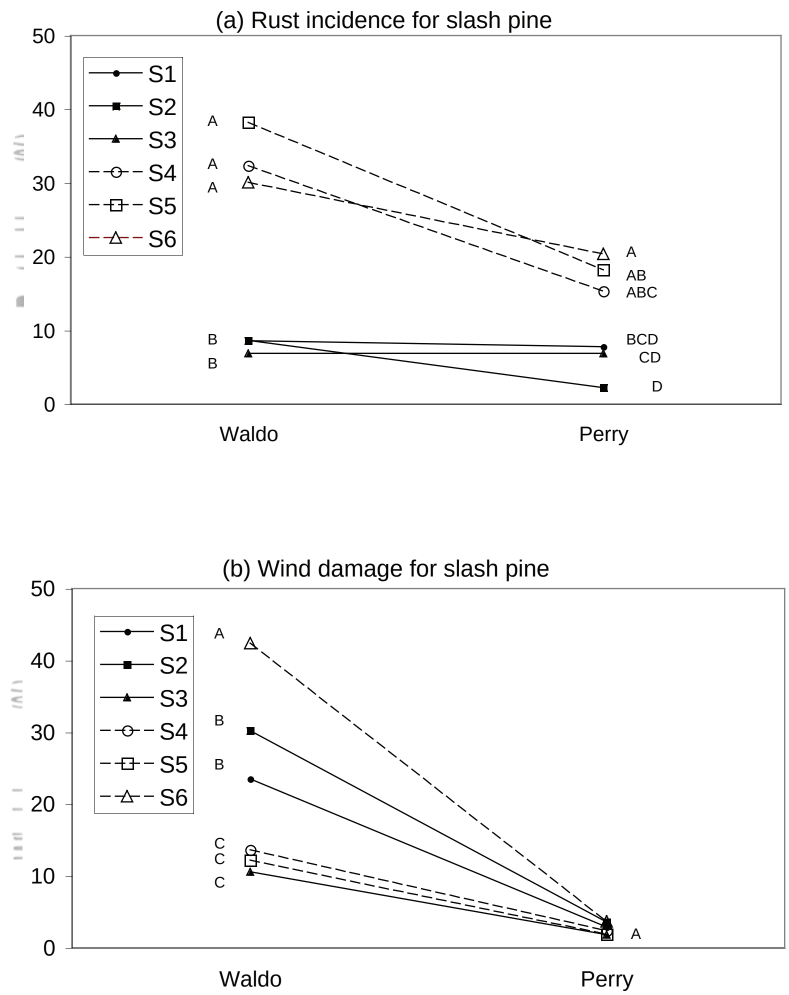

Figure 3—(a) Percent incidence of fusiform rust per plot at age five demonstrating a genotype x location interaction for slash pine (p=0.0189). Trees were considered infected if galls were noted on the branches or the main stem. (b) Percent incidence of wind damage per plot at age five, also demonstrating a significant genotype x location interaction for slash pine (p<0.0001). Trees were considered to be impacted by wind if they were leaning by more than 22 degrees from vertical or had a broken top. Data points within sites with the same letter are not significantly different at the 90% level of confidence using Bonferroni's Least Significant Difference (LSD).

are extremes in localized climatic conditions and/or pathogen populations. In the current study, through examination of damage codes made at the time of inventory, we were able to partially explain the G x E across sites for slash pine but not for loblolly pine. This does not totally explain the G x E in production as only two of the three families responsible for the G x E in rust occurrence (S4 and S6) corresponded to the GxE between sites in AGB at age five. In other words, two of the three families with a proportionally greater occurrence of rust at Waldo, FL also exhibited a lower than expected amount of AGB at age five at that same site. It is somewhat surprising that fusiform rust incidence did not explain the genotype x site interactions in loblolly pine given that the performance of resistant families of this species are the most unpredictable across sites (McKeand and others 2003).

Since all test sites were located within USDA Plant Hardiness Zone 8b, adaptation problems across sites should not be expected in this experiment (Schmidtling 2001, Lambeth and others 2005). One anomaly is the single slash pine family (S5), which had a greater incidence of fusiform rust occurrence at Waldo, FL (fig. 3a), yet similar biomass production when compared across locations (fig. 1b). The explanation for this anomaly may lie with its relative stability to the severe winds of 2004 (fig. 3b). In contrast, family S6 had the highest incidence of weather damage at the Waldo, FL site (42.4 percent), in combination with a fairly high occurrence of fusiform rust (30.1 percent). While there were large-scale effects of wind damage, there were no changes in rank among the slash pine families (fig. 3b). Occurrence of pitch canker, insect damage, and forking was examined, but did not explain the G x E observed in this study.

CONCLUSIONS

The significant genotype by location interactions as demonstrated in this study with limited genotypes and locations serves to emphasize the importance of carefully considering deployment and management of elite genotypes in the future. It follows that the best genotypes should be identified and deployed on the most suitable sites in combination with site- and genotype-specific silvicultural treatments. However, genotype deployment and silvicultural treatment decisions must also take into account localized pest and climactic conditions which may unexpectedly alter genotype performance.

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PINESTRAW RAKING, FERTILIZATION AND POULTRY LITTER AMENDMENT EFFECTS ON SOIL PHYSICAL PROPERTIES FOR A MID-ROTATION LOBLOLLY PINE PLANTATION

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Abstract—Frequent pinestraw raking and removal in pine plantations has led to concerns about nutrient removal from the stand. While soil chemistry of raked stands has been studied, little attention has been placed on potential compaction from raking operations. Four treatments were applied to a 16-year-old loblolly pine plantation at the Louisiana State University AgCenter Calhoun Research Station in Calhoun, LA: 1) No Rake and No Fertilizer, 2) Rake and No Fertilizer, 3) Rake and Commercial Fertilizer, and 4) Rake and Poultry Litter. Surface soil cores were sampled to assess treatment effects on soil bulk density, total porosity, moisture content, air-filled porosity, organic matter, and available water holding capacity. Raking significantly compacted the surface soil. Poultry litter significantly increased the soil moisture content over that of the commercially fertilized treatment. The unraked and unfertilized treatment and the commercially fertilized treatment had significantly greater air-filled porosity compared to the other two treatments. Raking with commercial fertilizer significantly reduced soil organic matter content from that of the control, but only from 0 to 2 inches depth. Trafficking effects from raking and fertilization operations are likely responsible for compaction effects on surface soils.

INTRODUCTION

Some forest landowners bolster forest products revenues of Southern pine plantations with occasional pinestraw raking. Fertilization of frequently raked stands has been recommended due to concerns about nutrient removals and alterations to soil chemistry. Fertilizing annually raked stands has been shown to maintain (Haywood and others 1995) or increase longleaf pine (*Pinus palustris* Mill.) pinestraw production (Dickens and others 1999) over that of unfertilized raked stands, presumably due to maintaining soil nutrition. However, little attention has been paid to potential compaction from raking and other non-harvesting operations.

Pinestraw has several possible impacts on soil physical properties, including increased water infiltration, reduced runoff and erosion, insulation of temperature and moisture regimes, increased available water-holding capacity, reduced evaporation, and decreased compaction (Duryea 2003, Taylor and Foster 2004). In a 16-year-old AR loblolly pine plantation, Pote and others (2004) found that annual pinestraw raking decreased infiltration rates, increased runoff, and increased erosion relative to less frequent raking. Within two weeks of complete litter removal in a longleaf pine stand, trees had lower xylem pressure potential and the soils had less moisture content than the unraked control (Ginter and others 1979). Longleaf pine growth was reduced in their study as well, and McLeod and others (1979) attributed the growth reduction to a disruption in the hydrologic cycle, rather than nutrient removals.

Poultry litter is generated in large quantities in many locations within the South, and it is being explored as a source for forest fertilization. There is concern that application of poultry litter will adversely impact water quality (Friend and others 2006). Not much information is available in the literature concerning poultry litter effects on soil physical properties (Brye and others 2004) or possible amelioration of raked soils by organic inputs such as poultry litter.

The objective of this study was to examine the effects of pinestraw raking and fertilizer source on soil physical properties of soil strength, bulk density, porosity, aeration, soil moisture content, organic matter, and available water holding capacity.

METHODS

The study was conducted in Calhoun, LA within a 16-year-old loblolly pine (*Pinus taeda* L.) plantation on the Calhoun Research Station of the Louisiana State University Agricultural Center. The trees were planted on a 16 by 6 feet spacing. The experimental design is randomized complete block design, with two blocks (soil type), each having eight 0.2-acre plots. Four treatments were imposed on four plots each: control (no raking and no fertilization), raking with no fertilization, raking with commercial fertilization (urea and diammonium phosphate), and raking with poultry litter as fertilizer.

The soils of the study area are the Ora and Savannah series, both fine-loamy, siliceous, thermic Typic Fragiudults (Matthews and others 1974). The study area was pasture (cattle paddocks) until 1990, when it was machine planted with loblolly pine, with no site preparation. The site was thinned in 2000 to a density of 250 trees per acre. Starting in fall 2000, the plantation was raked each fall using a tractor and mechanical raker and baler. Diammonium phosphate and urea (172 lbs per acre nitrogen, 115 lbs per acre phosphorus were applied in spring 2003, spring 2004, and fall 2005. Poultry litter was applied at those same times, at the same rates of nitrogen and phosphorus). Fertilizers were applied with a litter spreader.

Six surface (0-4 inches) soil cores were randomly sampled using the impact coring method (Blake and Hartge 1986) in April 2006 in each of the 0.2-acre plots. From these cores, the following were analyzed: bulk density, porosity, soil moisture content, and air-filled porosity. Six four-inch

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deep cores were randomly sampled within each plot in January 2007, using a soil probe. Each core was divided into 0-2 inch and 2-4 inch depths, which were analyzed for organic matter using the loss on ignition method (Nelson and Sommers 1996). Soil from additional randomly sampled 0-4-inch probe cores (six per plot) was composited by plot for construction of soil moisture retention curves, using the WP4 dewpoint potentiometer (Decagon Devices, Pullman, WA). Available water holding capacity was predicted from those curves. Soil strength was measured from April 28 to May 1, 2006, using the Field Scout SC 900 Soil Compaction Meter penetrometer (Spectrum Technologies, Inc., Plainfield, IL), with a mean of 18 randomly located profiles down to 12-inches depth within each plot. SAS (SAS Institute, Inc. 2006) was used to conduct analyses of variance of soil physical properties among the four treatments at a significance level of $P < 0.05$, using the protected Fisher's LSD procedure for mean comparison.

RESULTS

Mean surface bulk density for all treatments was compacted (greater than 1.65 g/cm^3), but the unraked and unfertilized control treatment had significantly lower bulk density as compared with that of the three raked treatments (table 1). Consequently, the control treatment had significantly higher total porosity compared with that of the three raked treatments. The raked and commercially fertilized treatment contained the lowest soil moisture content. The control and raked + commercial fertilizer treatments had significantly more mean air-filled porosity than that of the raked without fertilization and raked with poultry litter treatments.

The raked with poultry litter treatment had the lowest mean soil strength at 0-2 inches depth, and the raked with commercial fertilizer treatment had the highest mean soil strength (table 2). At 2-4 inches depth, soil strength was lowest in the control and raked with poultry litter treatments, and again highest in the raked with commercial fertilizer treatment, although not significantly different ($P = 0.1292$). The unraked and unfertilized control had significantly higher organic matter content relative to that of the raked + commercial fertilizer treatment, but at the 0-2 inches depth only. The unraked and unfertilized control contained the highest mean available water holding capacity, although not significantly different from the raked treatments ($P = 0.0561$).

DISCUSSION

Haywood and others (1995) found that winter and summer burning and annual harvesting of longleaf pinestraw on a Rapides Parish LA sandy loam soil (fine-loamy, siliceous, thermic Typic Paleudults) significantly increased bulk density over that of the unraked and unburned control, but fertilization did not. In a continuation of that study, Haywood and others (1998) found recovery of bulk density four years after halting annual pinestraw harvesting. On a Leadvale soil (fine-silty, siliceous, thermic Typic Fragiudults) in Logan County, AR, Pote and others (2004) investigated soil processes and water quality changes after annual raking of pinestraw from a 16-year-old loblolly pine plantation. Annual raking decreased infiltration, and increased runoff and erosion versus that of less frequently raked plots. However, where pinestraw had accumulated for at least two years, infiltration and erosion rates and runoff volume were similar to that of the control. Pote and others (2004) noted that after three years, pinestraw becomes matted by fungal growth. Raking less frequently (than annually) left significant amounts of partially decayed residue on the surface immediately after raking. The compaction and reduction in porosity observed in our study (table 1) resulting from annual pinestraw raking would undoubtedly influence infiltration and runoff, as was found in AR by Pote and others (2004). Similar to our finding of no significant change in organic matter (at 2-4 inches) from raking, commercial fertilizer, and poultry litter treatments, Ross and others (1995) found no effect from raking pinestraw or prescribed burning on surface soils under loblolly or longleaf pine plantations.

In the Delta region of eastern AR, Brye and others (2004) investigated effects of poultry litter form and rate on bulk density and soil water content for two silt loam soils and one silty clay soil. Only one of the silt loam soils experienced a bulk density decrease in the upper four inches as litter rate increased. None of the three soils' volumetric water content was increased by increasing poultry litter rates. Nonetheless, the authors concluded that poultry litter has positive short-term effects on soil physical properties, and that the water content may be more sensitive for coarser-textured soils. Five years after application of sewage-sludge compost with beef manure on a sandy MD upland Coastal Plain soil, soil strength and bulk density were significantly reduced, and soil water content was increased as compared with that of the control (Tester 1990). For our study, poultry litter application significantly increased volumetric soil water content over that of raking with commercial fertilization (table 2). Poultry litter application also greatly reduced soil strength in the upper four inches, as compared with the other two raking treatments (table 2).

The main effects of raking pinestraw at the Calhoun Research Station on soil physical properties were increased bulk density and decreased porosity. The raked treatment with commercial fertilization had the lowest soil moisture content. Poultry litter application on raked soils increased the organic matter relative to the other two treatments that included raking, but not significantly. Although poultry litter addition reduced soil strength, it also had significantly lower air-filled porosity than the control and raking with commercial fertilizer. Poultry litter ameliorated some soil physical properties resulting from raking pinestraw, but not significantly. These effects on the soil physical properties are important factors when considering their impacts on soil microbial biomass and activity. The soil's capacity to provide favorable conditions, particularly adequate soil oxygen and moisture, for biological activity are fundamental to sustaining forest productivity. It remains to be seen what effects continued annual pinestraw raking and fertilization will have on surface soils, and for how long. Ongoing research on the relationship between observed soil physical effects as well as chemical effects from pinestraw removal and chemical amendments on microbial processes will increase

Table 1—Means of surface (0-4 in. core) soil physical properties for four treatments applied to a mid-rotation loblolly pine plantation at Calhoun, LA. Means with the same letter within a column are not significantly different at α=0.05

Treatment	Bulk Density	Porosity	Moisture	Air-filled Porosity
	g/cm³	*volume %*	*volume %*	*volume %*
Control (No Rake, No Fertilize)	1.67 b	36.9 a	27.0 ab	9.9 a
Rake, No Fertilize	1.81 a	31.8 b	26.8 ab	5.0 b
Rake, Commercial Fertilize	1.76 a	33.4 b	24.8 b	8.6 a
Rake, Poultry Litter	1.78 a	32.8 b	28.1 a	4.8 b

Table 2—Means of surface soil properties for four treatments applied to a mid-rotation loblolly pine plantation at Calhoun, LA. Means with the same letter within a column are not significantly different at α=0.05

Treatment	Soil Strength *psi*		Organic Matter %		Available Water Holding Capacity %
	(0-2 in.)	(2-4 in.)	(0-2 in.)	(2-4 in.)	(0-4 in.)
Control (No Rake, No Fertilize)	180.6 b	341.7 a	2.78 a	2.31 a	42.65 a
Rake, No Fertilize	334.5 a	506.9 a	2.58 ab	2.01 a	36.65 a
Rake, Commercial Fertilize	355.8 a	522.3 a	2.25 b	1.90 a	35.35 a
Rake, Poultry Litter	144.0 b	358.2 a	2.58 ab	2.19 a	38.40 a

our understanding of the ecological sustainability of these practices.

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INITIAL RESPONSE OF LOBLOLLY PINE AND COMPETITION TO MID ROTATION FERTILIZATION AND HERBICIDE APPLICATION IN THE GULF COASTAL PLAIN

Hal O. Liechty and Conner Fristoe[1]

Abstract—Application of N and P to mid-rotation loblolly pines (*Pinus taeda* L.) stands is a common silvicultural practice used to increase crop tree production in the Gulf Coastal Plain. Mid-rotation applications of herbicides or combined applications of herbicide and fertilizer are a less common practice. We applied herbicide (1.17 l imazapyr and 0.23 l surfactant/ha) and fertilizer (409 kg-urea and 196 kg-diammonium phosphate/ha) to four mid-rotation stands (17- to 22-years-old) in southern AR and northern LA to evaluate the response of pine and woody competition to each of these treatments as well as a combination of these two treatments. Three years after initial herbicide application 50 to 83 percent of the initial woody competition had died. Mortality of the woody competition from the herbicide application was significantly greater with the addition of fertilizer than without. Net pine basal area and merchantable volume growth was increased. Net basal area growth 2 to 3 years after initial treatment application was 10 to15 percent greater with fertilization than without. Net volume growth was greatest with the combined herbicide and fertilization treatment.

INTRODUCTION

Nitrogen and phosphorus are the most limiting nutrients for loblolly pine growth in the Southern United States (Schultz 1997). Growth of loblolly pine can be significantly enhanced by applications of these nutrients during several stages of stand development. In the Gulf Coastal Plain, Sword-Sayer and others (2004) found that fertilization at ages of 11 and 17 increased biomass production of a loblolly pine stand by 43 to 48 percent. Other studies in this region have found significant but smaller volume or diameter growth responses to fertilization (Haywood and Tiarks 1990, Williams and Farrish 2000, Bataineh and others 2006). Weed control (woody and herbaceous) following stand establishment can also increase crop tree growth. Continuous weed control during the first 3 to 6 years following plantation establishment has been found to cause greater volume growth responses than fertilizer at these early stand ages (Borders and Baily 2001). Combinations of weed control with fertilization during these early periods of stand development usually provide the greatest pine growth responses (Borders and Baily 2001, Borders and others 2004). However, weed control and/or applications of herbicide in later stages of stand development have not always been found to improve loblolly pine growth. Williams and Farrish (2000) did not find a significant response to herbicide application when applied in 25 to 26 or 30 to 32-year-old stands in Louisiana. Diameter and volume growth was not significantly increased during the first four years following herbicide application in an 18-year-old loblolly pine plantation located in Texas (Bataineh and others 2006). Although growth responses of mid-rotation stands in some studies have been optimized by a combination of fertilization and herbicide application (Albaugh and others 2003) most studies in the Gulf Coastal Plain has shown no additive effects from the combination of these treatments (Williams and Farrish 2000, McInnis and others 2004, Bataineh and others 2006). To better understand the impacts of fertilization and herbicide application on loblolly pine growth and productivity within the Upper Gulf Coastal Plain, we established a study in four mid-rotation loblolly stands located in AR and LA.

METHODS

Study Site

The stands are located in the Upper Gulf Coastal Plain of AR and northern LA. Soils on the sites are either Paleudults or Fraglossudalfs. Three of the stands were plantations and were either planted to 1682 or 1793 trees/ha in 1985. The other stand was a natural stand and regenerated by seed tree regeneration. The seed trees at this site were removed in 1981. Each stand was thinned in either 2000 or 2001, one or two years prior to study establishment.

Experimental Design and Treatment

Twelve plots (between 0.06 and 0.10 ha) plots were established at each site (W. Crossett, S. Crossett, Marion, and Crossroads) during 2001 or 2002. All trees or other woody vegetation with a diameter at breat height (d.b.h.) $\geq$2.54 cm were permanently tagged and given a unique number. Herbicide (1.17 l imazapyr and 0.23 l surfactant/ ha in 140.3 l/ha of water) was aerially applied during the fall following plot establishment to half the plots as well as a 50-m buffer around each plot. During January or February following the first growing season after herbicide application, 409 kg/ha of urea and 196 kg/ha of diammonium phosphate was applied to three plots and associated buffers that received the herbicide treatment and three that did not receive the herbicide treatment. Fertilizer was applied by hand at each plot.

Measurements and Statistical Analysis

D.b.h. of each tree and heights of each pine tree (d.b.h. $\geq$2.54 cm) in a plot were recorded prior to or just after herbicide application. D.b.h. of each tagged tree was measured annually and total height of each tagged pine tree was measured biennially there after. Mortality of the hardwoods (woody competition) was assessed annually during the early portion of the growing season. Ingrowth (d.b.h. $\geq$ 2.54 cm) of hardwood and other woody competition was assessed and tagged biennially after initial plot establishment. Total pine

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outside bark volume and total merchantable outside bark volume was computed biennially using volume equations by Amateis and Burkhart (1987). Total merchantable volume was calculated to a 7.62-cm top for trees with a d.b.h. greater than or equal to 14.2 cm. The experimental design of the study was a split plot with the herbicide treatment being the whole plot. Analysis of variance was used to determine differences between herbicide and fertilizer treatments. If there was a significant interaction, Tukey's mean separation test was used to determine differences between herbicide, treatment combinations. To evaluate differences in the proportion of hardwood mortality between fertilized and unfertilized herbicide treatment combinations, a Kolmogorov-Smirov nonparametric test was used. All statistical tests were perform using $\alpha = 0.05$.

RESULTS AND DISCUSSION

Initial Stand Conditions

Initial pine and hardwood density varied considerably among the four sites. Pine basal area was respectively 26.8, 16.5, 12.9 and 16.0 m^2/ha at the W. Crossett, S. Crossett, Marion, and Crossroads site. Hardwood basal area was the greatest at the Crossroads site (3.2 m^2/ha) and least at the South Crossett site (0.7 m^2/ha). Pine density was between 488 to 1291 trees/ha while hardwood density was between 366 to 833 trees/ha.

Hardwood Mortality

By the end of the third growing season following herbicide application, 50 to 80 percent of the hardwood basal area in plots receiving the imazapyr treatments had died (fig. 1). Only 2.4 percent of the hardwood basal area died in the plots that did not received herbicide. The proportion of hardwoods that died in a plot following the application of imazypyr was negatively correlated with the basal area of pine within a plot prior to imazypyr application. A simple regression equation (1) fitted to the cumulative hardwood basal area mortality during the first two years of the study indicated that the predicted hardwood mortality would be between 31 to 58 percent over the range of initial plot pine basal areas (28.4 to 11.4 m^2/ha) observed in the study. These results suggest that increased pine density increases non-target species interception of herbicide and thus reduces the amount of herbicide delivered to the hardwood foliage or soil which results in reduced hardwood mortality. Increasing the amount of water applied with the herbicide in stands with high pine densities may increase the transport of the herbicide to the hardwood competition thereby increasing hardwood mortality to more acceptable levels.

$$PHBAM = -0.0136 + 0.7033\ IPBA \qquad r^2 = 0.173 \qquad (1)$$

where: PHBA = Proportion of hardwood basal area mortality

IPBA = Initial pine basal area

Hardwood mortality was also impacted by fertilization. After three growing seasons hardwood mortality in the herbicided plots that were not fertilized averaged 1.20 but 1.42 m^2/ha on plots receiving both herbicide and fertilizer. The proportion

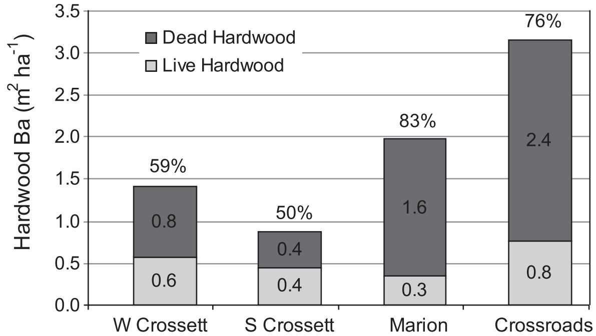

Figure 1—Basal area of hardwood and woody competition that was alive and died by the end of the third growing season following herbicide application at four sites in the Upper Gulf Coastal Plain.

of initial hardwood basal that died during the first three years following herbicide application was consistently higher with fertilization (75.1 percent) than without fertilization (62.2 percent) for all sites (fig. 2). These differences were significant. Increases of hardwood mortality with fertilization are likely related to increased competitive ability of the pine. Nutrient amendment increases leaf area index of pine, which would likely reduce the amount of light and decrease available water for understory hardwood competition.

Pine Growth

Herbicide application did not significantly increase basal area growth of the pine during the first two years of the study (table 1). Basal area growth was significantly increased by the fertilization treatment. Although fertilizer was only applied during the start of the second year of the study, average annual basal area growth was 1.72 m^2/ha per year in the fertilized plots compared to 1.56 m^2/ha per year in plots without fertilization. This represented an overall 10 percent increase in growth during the initial two years of the study. Herbicide application appeared to decrease height growth while fertilizer had no effect on height growth of the pine during the first two years following study initiation. Average annual height growth was respectively 0.55 m with and 0.79 m without herbicide application. Short term stunting of pine height growth following application of imazypyr has also been reported in other studies (Quicke and others 1996). Although

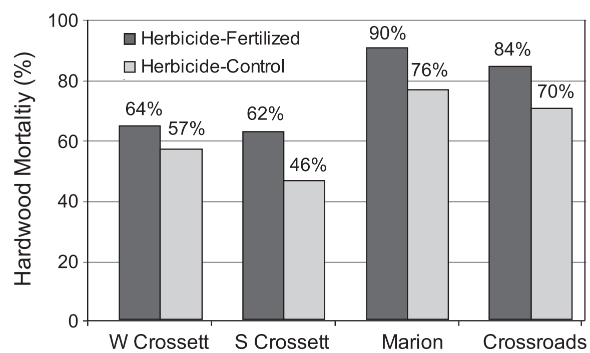

Figure 2—Cumulative proportion of hardwoods and woody competition that died by the end of the third growing season following herbicide application by fertilization treatment at four sites in the Upper Gulf Coastal Plain.

Table 1—Mean net annual pine growth (standard deviation) during the first two years of the study for each treatment combination at four study sites

Net Annual Growth	Control	Herbicide	Fertilizer	Herbicide+Fertilizer
Basal Area (m^2/ha)	1.53(0.24)	1.60(0.39)	1.63(0.23)	1.81(0.24)
Height (m/ha per year)	0.78(0.34)	0.52(0.33)	0.80(0.27)	0.58(0.30)
Total Volume (m^3/ha per year)	18.0(3.5)	15.5(4.3)	18.5(2.6)	18.0(3.8)
Merchantable Volume (m^3/ha per year)	19.2(3.0)	16.6(4.1)	19.3(2.4)	19.5(2.8)

the reduction in height growth was approximately 30 percent, differences were not significant. The lack of a statistically significant difference in height growth compared to basal area (d.b.h.) growth likely reflects the larger errors associated with height measurement compared to d.b.h. measurement.

Net total volume growth was consistently less than merchantable volume growth (table 1) due to the mortality of unmerchantable pine trees and ingrowth of trees into the merchantable size class. Trees that died were generally suppressed and were of low vigor prior to treatment applications. There was no significant response of net total volume growth to either the fertilizer or herbicide application. Annual total volume growth was very similar among the control, fertilizer, and fertilizer + herbicide treatments. The fertilization and herbicide interaction term was significant for net annual merchantable volume growth. Multiple range tests ranked merchantable volume growth in the following order: herbicide < control = fertilizer < fertilizer + herbicide. The poor growth of trees receiving herbicide in part was due to the higher rates of mortality associated with this treatment. Total merchantable volume mortality during the two year period was respectively 0.00, 0.63, 0.00, and 0.18 m^3/ha for the control, herbicide, fertilization, and fertilization + herbicide treatments. Application of fertilizer appeared to mitigate the initial impacts of the herbicide application on merchantable volume growth but when applied without herbicide did not appear to enhance growth. Thus the combined fertilizer and herbicide treatment had the highest merchantable volume growth rate but differences between the combined treatment and control were relatively minor.

Three year basal growth responses could only be assessed for the W. Crossett, S. Crossett, and Crossroads sites because the pine at the Marian site was mistakenly thinned during the third growing season. Net basal area growth treatment responses for this three year period were similar to that for the first two growing seasons. Net basal area growth was significantly greater with fertilization than without (1.84 vs. 1.63 m^2/ha per year). Fertilization increased net basal area growth by 13 percent but herbicide application had no significant effect on growth. The combined fertilizer and herbicide treatment consistently had the greatest growth but the interaction term in the ANOVA was not significant.

The lack of positive growth responses associated with herbicide application during the two to three year response period reported above are similar to that observed for a majority of sites evaluated by Albaugh and others (2003) and studies reported by Williams and Farrish (2000) and Bataineh and others (2006). Reponses to herbicide especially when applied with fertilizer frequently occur over greater periods of time (4 to 8 years) than was assessed in our study (Fortson and others 1996, Quicke and others 1996). The rapid growth responses associate with fertilization emphasize that these sites were nutrient limited and the benefit of fertilization in upper Gulf Coastal Plain pine plantations.

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IMPACT OF PRUNING INTENSITY ON GROWTH OF YOUNG LOBLOLLY PINE TREES: SOME EARLY RESULTS

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Abstract—In the spring of 2000, a designed experiment was established to study the effects of pruning intensity on the growth of loblolly pine (*Pinus taeda* L.) trees. Trees were planted at a 1.83 by 1.83 m square spacing in plots of eight rows with eight trees per row; the inner 36 trees constituted the measurement plot. Four blocks containing five treatment plots were established at each of two locations in the Virginia Piedmont. The five treatment plots included an unpruned control, and pruning treatments where 1/4 of the live crown was removed on all the trees, 1/2 of the live crown was removed on all the trees, 1/4 of the live crown was removed on 1/2 of the trees, and 1/2 of the live crown was removed on 1/2 the trees. Measurements at the time of treatment and one year after treatment for each tree included d.b.h., total height, height to base of live crown, crown width within and between the row. Results are presented that show the initial impact of pruning on tree growth. Additional measurements gathered over the life of the study will provide a more complete understanding of the effects of pruning on development of loblolly pine trees.

INTRODUCTION

Pruning affects wood quality of trees harvested from loblolly pine plantations (Gibson and others 2002). Pruning future crop trees during stand development removes limbs (both living and dead) that produce knots in wood products merchandized from harvested logs. Removing live branches may also affect the onset of the production of mature wood and thus change the density and strength properties of wood obtained from pruned trees. By improving wood quality, pruning has been shown to be profitable given certain economic assumptions (Huang and Kronrad 2004).

Pruning live limbs also affects tree growth and stand development. Valenti and Cao (1986) showed that pruning reduced stem taper resulting in more cylindrical trees with more volume per tree. Burton (1981) as well as others such as Labyak and Schumacher (1954) and Marts (1949) showed that pruning vigorous, live limbs causes a real and significant effect on stem form and subsequent diameter growth, at least for a period of time following pruning.

For the most part, past studies on the impact of pruning on tree form and growth have been conducted in stands without intensive silviculture. Today's plantations are being intensively managed using cultural practices that produce very rapid growth rates, thus allowing pruning treatments to be applied earlier in the rotation when trees are growing most rapidly. It is unclear what impact pruning will have on these intensively managed stands, and how they will grow and develop following treatments.

In order to examine the impact of pruning on loblolly pine trees growing in intensively managed plantations, a pruning study was established to examine the effect of pruning intensity on tree growth and stand development. In this paper we present some early results from this study.

DATA

In the spring of 2000, two study sites in the Piedmont of VA (Appomattox and Patrick Counties) were identified as being suitable for establishment of the study. Both sites were cutover areas, one of which was burned following harvest. At each site, four replications containing five future treatment plots were laid out and planted using genetically improved 1-0 loblolly pine seedlings. The five future treatments included (1) control (unpruned), (2) removing 25 percent of the live crown on all the trees, (3) removing 50 percent of the live crown on all the trees, (4) removing 25 percent of the live crown on half the trees, (5) removing 50 percent of the live crown on half the trees. Square treatment plots (eight rows with eight trees per row) were established; the interior thirty-six trees were measurement trees.

Herbicides were applied during the first two years after planting to control competing vegetation. Elemental nitrogen at 225 kg/ha and 22 kg/ha of elemental phosphorus were applied at age 2 to all plots. Annual measurements from age 2 included d.b.h., height to live crown, total height and two measures of crown width. Pruning treatments were applied at age 6. For treatments (4) and (5), the choice of which trees to prune was made systematically: tree 1 in row 1 was randomly determined to be pruned or not pruned and then every odd-numbered tree in the plot received the same treatment as tree 1. The even-numbered trees in the plot received the other treatment. Thus, following treatment, each tree in the plot was surrounded by four adjacent neighbors having the other treatment. Table 1 presents summary statistics by treatment at time of treatment (age 6).

ANALYSES

A model was specified to examine tree growth following treatment (from age 6 to age 7) and stem form using analysis of variance techniques:

$$G = b_0 + b_1Loc_i + b_2Rep_j + b_3T_k + E_{ijk} \quad (1)$$

where G is the periodic annual growth (PAI) of d.b.h, total height and average crown width between age 6 and 7, and also the height over d.b.h. ratio at age 7. Loc is the location effect (Appomattox or Patrick County, VA), Rep is the Replication effect, T is the treatment effect (control or one of the four pruning treatments) and E is the error term. All statistical tests were made at the α=0.05 significance level.

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Table 1—Before and after pruning statistics at time of pruning (age 6) for the four pruning treatment plots and the control plot

	Before pruning		After pruning	
	Mean	Std. dev.	Mean	Std. dev.
	-------------- Control ------------			
Dbh (cm)	8.40	1.74		
Height to live crown (m)	1.42	0.58		
Total height (m)	5.59	0.89		
Crown width (m) [a]	2.45	0.39		
	- Prune 25% of Live Crown on All the Trees -			
Dbh (cm)	8.10	1.89		
Height to live crown (m)	1.35	0.61	2.46	0.62
Total height (m)	5.51	0.94		
Crown width (m) [a]	2.47	0.39	2.24	0.39
	- Prune 50% of Live Crown on All the Trees -			
Dbh (cm)	8.31	1.88		
Height to live crown (m)	1.39	0.68	3.53	0.81
Total height (m)	5.62	1.04		
Crown width (m) [a]	2.46	0.42	1.85	0.42
	- Prune 25% of Live Crown on ½ the Trees -			
Dbh (cm)	8.18	1.92		
Height to live crown (m)	1.33	0.59	2.45	0.62
Total height (m)	5.43	0.93		
Crown width (m) [a]	2.45	0.42	2.27	0.37
	- Prune 50% of Live Crown on ½ the Trees -			
Dbh (cm)	7.88	1.89		
Height to live crown (m)	1.35	0.67	3.39	0.76
Total height (m)	5.42	0.99		
Crown width (m) [a]	2.36	0.44	1.80	0.43

[a] Average of within and between row crown widths

From age 6 to age 7, PAI for d.b.h. and average crown width were significantly different between the treatments. There was also a significant difference between treatments for the height over d.b.h. ratio at age 7. PAI for height, however, was not significantly different between the treatments (Table 2).

A second model was specified to examine the growth of the pruned trees (P) in the two plots where one-half the trees were pruned and the other half were unpruned:

$$G = b_0 + b_1 Loc_i + b_2 Rep_j + b_3 P_l(T)_k + E_{ijkl} \qquad (2)$$

where P is the group of trees pruned within treatment plot, T (the plots where 25 percent of the crown was pruned on half the trees or 50 percent of the crown was pruned on half the trees), and other variables are as previously defined. D.b.h., and mean crown width PAI from age 6 to age 7 were significantly different between the pruned and unpruned trees in these two treatment plots. Likewise, the mean height over d.b.h. ratio was significant. However, the mean total height PAI was not significant. Table 3 presents these results.

DISCUSSION AND CONCLUSIONS

The pruning treatments applied in this study range from light (removing 25 percent of the crown length on half the trees) to very severe (removing 50 percent of the crown length on all the trees). At age 6, the time of treatment, the plots had a closed canopy and crowns of adjacent trees were touching. Intraspecific competition had begun and crowns were beginning to recede. Removing 25 percent of the live crown length appeared to reduce crown mass, or volume, by about 30 percent on an individual tree basis, but still left the plot with a closed canopy. Removing 50 percent of the live crown length appeared to reduce crown mass by considerably more, perhaps on the order of 60 to 70 percent and greatly opened up the canopy of the plot. This was especially true on

Table 2—Periodic annual increment (standard deviation in parentheses) for dbh, total height and mean crown width; mean height over dbh ratio for the control and four pruned treatment plots (P value for F-test between treatment means)

Variable	Control	Prune 25% on all trees	Prune 50% on all trees	Prune 25% on half the trees	Prune 50% on half the trees	P value
PAI dbh (cm)	1.51(0.36)	1.41(0.36)	1.07(0.37)	1.46(0.37)	1.33(0.50)	<.0001
PAI total height (m)	1.23(0.30)	1.22(0.34)	1.20(0.28)	1.21(0.28)	1.20(0.26)	0.4960
PAI mean crown width (m)	0.13(0.25)	0.32(0.28)	0.60(0.32)	0.24(0.25)	0.41(0.32)	<.0001
Height over dbh ratio (m/cm)	0.70(0.10)	0.73(0.11)	0.74(0.10)	0.71(0.11)	0.74(0.11)	<.0001

Table 3—Periodic annual increment (standard deviation in parentheses) for dbh, total height and mean crown width; mean height over dbh ratio for the pruned and unpruned tree groups within the prune 25% of the live crown on half the trees and the prune 50% of the live crown on half the trees treatment plots (P value for F-test on the means between pruned and unpruned trees within treatment plots)

	Prune 25% on half the trees		Prune 50% on half the trees		
Variable	Unpruned trees	Pruned trees	Unpruned trees	Pruned trees	P value
PAI dbh (cm)	1.51(0.41)	1.41(0.33)	1.60(0.45)	1.06(0.39)	<.0001
PAI total height (m)	1.19(0.30)	1.22(0.25)	1.23(0.26)	1.16(0.26)	0.0778
PAI mean crown width (m)	0.18(0.23)	0.30(0.25)	0.26(0.24)	0.55(0.32)	<.0001
Height over dbh ratio (m/cm)	0.72(0.13)	0.70(0.09)	0.72(0.10)	0.76(0.12)	0.0096

the plot where 50 percent of the crown length was removed on all the trees. The trees appeared to respond to the pruning treatment as they would to a thinning, with greater rates of lateral crown expansion.

D.b.h. growth in the year following treatment was significantly less for the more intensively pruned plots. These findings suggest that pruned trees will allocate growth firstly to crown growth and secondly to diameter growth.

Interestingly, height growth was not significantly impacted by pruning. Even though a large portion of the crown was removed in the heavily pruned plots, resources were still adequate for achieving height growth that was not significantly different from the control. In a companion study (Amateis and Burkhart 2006) severe pruning at age 3 was found to significantly reduce height growth. Apparently, at this particular point in stand development, trees that have been severely pruned will still maintain normal height growth despite losing a large portion of their photosynthetic capacity.

Since height growth was maintained while diameter growth diminished, the height over d.b.h. ratio was slightly larger for the pruned plots. Thus, stem form has been altered by pruning even after only one year following treatment.

In the plots where half the trees were pruned and half were not pruned, results were similar. Within these plots, the mean height growth of the pruned trees was not significantly different from the unpruned trees, even though each pruned tree had four nearest neighbors that were unpruned. Diameter growth was significantly less for the pruned trees than for the unpruned trees, and thus the height over d.b.h ratio was larger for pruned than for unpruned trees within these plots.

If these early results persist they suggest that pruning all trees in a stand and even pruning some trees in a stand at an early age when height growth is vigorous may be viable treatments for improving wood quality and stem form.

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EFFECTS OF PRECOMMERCIAL THINNING IN NATURALLY REGENERATED LOBLOLLY-SHORTLEAF PINE STANDS IN THE UPPER WEST GULF COASTAL PLAIN: RESULTS AFTER TWO GROWING SEASONS

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Abstract—The benefits of precommercial thinning in naturally regenerated stands of southern pines have been well documented, but questions remain about how long precommercial thinning can be delayed and still be biologically and economically effective. In 2004, a precommercial thinning demonstration study was installed in naturally regenerated loblolly-shortleaf pine (*Pinus taeda* and *P. echinata*, respectively) stands that were 8, 14, and 19 years old. Treatments consisted of three levels of precommercial thinning with an unthinned control. Precommercial thinning promoted the growth of individual pines; dominant trees in the lowest retained densities annually grew 0.05 to 0.07 square feet in basal area regardless of stand age. However, stand-level growth was greatest for moderate densities because more trees occupied the site, offsetting the lower rates of tree growth. Tree mortality increased with increasing density and was a major element of stand dynamics. These results from our study provide foresters and landowners with a first look at the implications of delayed precommercial thinning with respect to individual tree and stand growth.

INTRODUCTION

The value of precommercial thinning in naturally regenerated stands of southern pines has been well documented for the Upper West Gulf Coastal Plain. Precommercial thinning of natural stands of loblolly-shortleaf pines (*Pinus taeda* and *P. echinata*, respectively) at age 6 significantly increased volume growth by age 19 (Cain 1996) and sawtimber production at age 25 (Cain and Shelton 2003). These publications are based on an ongoing study established in 1980 on the Crossett Experimental Forest in southeastern AR, but that study has now aged to the point that it no longer has value as a demonstration of recent precommercial thinning treatments. In addition, there are other questions appropriate for consideration by private landowners: how long can precommercial thinning be delayed and remain an effective tool; what are the costs of treatments in stands where stems vary in size; and what comparable returns in growth, stand development, and added value over time can be expected above and beyond the alternative of no treatments?

An even-aged regulation demonstration was established on two 40-acre stands on the Crossett Experimental Forest in 1980, and they offered an opportunity to answer these questions. The demonstration imposed a prescription that consists of clearcut and seed-tree reproduction cutting methods applied sequentially in 5-acre blocks and strips during successive 5-year cutting cycles over a 40-year period. Each block and strip harvested to date has resulted in successful pine regeneration, and tree density in all blocks and strips far exceeded that which is needed for development of fully stocked stands.

As of 2004, none of these stands had been precommercially thinned. However, conventional recommendations for precommercial thinning call for treatment by age 5 to a residual density of 500 to 700 trees per acre (Baker and Langdon 1991). That leads to the question of whether and when precommercial thinning is needed to properly regulate tree density, and thereby to accelerate the development of the new cohort into pulpwood and sawtimber size classes. In the current study, a two-replication demonstration approach was used to evaluate the effects of precommercial thinning in different age cohorts in the even-aged regulation demonstration. Our objective was to quantify and demonstrate the growth response that can be expected when thinning even-aged, naturally regenerated stands of loblolly-shortleaf pine in the Upper West Gulf Coastal Plain to different residual density levels at ages older than conventionally are recommended.

METHODS

Study Site and Management History

The study is located within two 40-acre loblolly-shortleaf pine stands on the Crossett Experimental Forest in Ashley County, AR at 33° 02' N mean latitude and 91° 56' W mean longitude. Soil series are Bude (Glossaquic Fragiudalfs) and Providence (Typic Fragiudalfs) silt loams (Gill and others 1979). These soils have a site index of 85 to 90 feet for loblolly pine at age 50 years. Elevation is about 130 feet with nearly level topography. Annual precipitation averages 55 inches with seasonal extremes being wet winters and dry autumns. The study area is typical of productive sites for mixed stands of loblolly and shortleaf pines growing in the Upper West Gulf Coastal Plain.

From the mid-1930s through the 1960s, the areas were managed using single tree selection, which involves periodic harvests of the poorest quality trees while retaining the best trees in certain size classes for future harvests and natural seeding (Reynolds 1969). The areas were not managed from 1970 to 1980 and became overstocked (basal area over 100 square feet per acre) with pines ranging from 10 to 24 inches diameter at breast height (d.b.h.). When the areas were selected for study installation in 1980, there was a mixture of

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midstory and understory hardwoods beneath a closed pine canopy.

Each 40-acre stand was subdivided into eight 5-acre subunits. One stand was subdivided into strips (165 by 1,320 feet) and the other into blocks (330 by 660 feet) with the long axes being oriented north and south. At approximately 5-year intervals, even-aged reproduction cutting of two subunits (one strip and one block) per interval proceeded across the stands in a westerly direction to ensure that pine seeds from the residual stand would be dispersed by prevailing northwesterly winds into the subunits being cut.

Regeneration cohorts used in this study developed from seed crops principally dispersed during the autumn of 1980, 1985, 1990, and 1996; these years are used to designate the subunits established in the block and strip management areas. Reproduction cutting either occurred concurrently with seed dispersal in the autumn (1985 and 1996) or in the following spring (1981 and 1991). In the same operation as the reproduction cut, the remaining portion of the original stand in each management area was thinned to a residual basal area of 80 square feet per acre, cutting trees mainly in the lower crown classes. Clearcutting was used for the 1980 cohort in both the block and strip. Subsequently, the strips were regenerated using clearcutting, and the blocks were regenerated using the seed-tree method by retaining 10 to 15 seed trees per acre. The seed trees in the 1985 and 1990 blocks were cut after 5 years, but seed trees were retained in the 1996 block.

To promote natural pine reproduction, prescribed winter burns were periodically conducted to top-kill understory hardwoods and create a favorable pine seedbed by reducing forest floor litter. Burns were conducted in March 1980, October 1981, November 1986, February 1987, December 1989, and December 1995. All 5-acre subunits that had previously received reproduction cutting were excluded from burning after an initial site-preparation burn. In the summer of 1980, hardwoods were controlled by basal stem injection with herbicides in the two subunits designated for reproduction cutting. Likewise in summer 1984, hardwoods were controlled with a soil-applied herbicide in the two designated subunits. However, no herbicides were used in the 1990 and 1996 cohorts because the repeated fires had effectively controlled understory hardwoods and markets existed then for hardwood pulpwood, which enabled cutting midstory hardwoods. Cain and Shelton (2001) provided additional detail on the site preparation techniques employed in the study area.

Treatments

In early summer 2004, each regenerated 5-acre strip and block for the 1985, 1990, and 1996 cohorts was subdivided into four 1.25-acre treatment plots (165 by 330 feet), and four treatments were randomly assigned within the strip and block management areas separately. The thinning treatments, conducted precommercially (that is, no harvested material was removed from the site), consisted of three levels of mechanical or geometric thinning (Smith and others 1997, Helms 1998) with an unthinned control. Three methods of precommercial thinning were used: (1) chain-saw felling to a designated operational target of residual stems (100, 200, or 400 stems per acre) based on tree spacing by contract crews, (2) one-pass mowing using a farm tractor with bush-hog attachment to cut a 6-foot-wide swath and leaving a 2-foot strip between swaths and conducted by staff of the Crossett Experimental Forest, and (3) two-pass mowing as previously described but with swaths occurring at right angles. Treatments were implemented from June 1 to June 6, 2004. Treatments for the 1996 cohort were 200 trees per acre, two-pass mowing, one-pass mowing, and an untreated control. Treatments for the 1985 and 1990 cohorts were 100, 200, and 400 trees per acre and an untreated control.

No precommercial treatments were implemented in the 1980 block and strip cohorts, which were damaged by an ice storm in December 1998 (Cain and Shelton 2002, Bragg and others 2003). However, little or no damage occurred in the younger blocks and strips. The 1980 cohorts were commercially salvaged and thinned to about 200 crop trees per acre the year following ice damage. Data from these areas are included for comparative purposes.

Measurements and Analysis

For each 1.25-acre treatment plot receiving precommercial thinning or their controls, four 0.05-acre circular (26.3-foot radius) subplots were established along the long axis of the center line. Only two subplots were located in the 200 trees per acre, 1996 block, because the subplots fell within a pre-existing streamside management zone. Four 0.05-acre subplots were also located within the 1980 strip and block. On each subplot, all residual pine and hardwood stems 0.6-inches d.b.h. and larger were tagged with a prenumbered round aluminum tag, and a mark was painted at 4.5 feet aboveground. Subplot establishment and measurement began on September 7, 2004 and was completed on June 28, 2005. Subplots measured during the early part of the 2005 growing season included one subplot of the one-pass treatment in the 1996 block, the four control subplots of the 1996 block, and all subplots of the strip management area except the 1980 cohort. Tagged stems were measured for d.b.h. and species was recorded. Tagged stems were remeasured for d.b.h. from September 13, 2006 through November 2, 2006; mortality was recorded. Any untagged stems growing past the 0.6-inch d.b.h. threshold were tagged, d.b.h. measured, and species recorded.

Eight 0.05-acre subplots existed for all ages and treatments except for the 200 trees per acre, 1996 block for which there were six subplots. For each subplot, density, basal area, and mean d.b.h. were calculated by pine and hardwood components; these values were then averaged by treatment and age and standard errors calculated. No existing pine seed trees were included in the calculations. The growth of individual trees was modeled according to the procedure of Murphy and Shelton (1996). Stand-level variables for the model were from the specific 0.05-acre subplot that the subject tree occurred on. An indicator variable (Rao 1998) was included in the model to account for the late first measurement occurring on some subplots (May 12, 2005 through June 28, 2005). Data from the 1980 cohort were not included in the model. Equation coefficients were obtained from nonlinear ordinary least squares regression using SAS procedure MODEL (SAS 1988).

Variables were dropped from the equation if their coefficients did not differ from zero at $P < 0.05$. When measurements began at the end of the 2004 growing season, the reproduction cutting employed resulted in a series of even-aged natural stands that were 8 (1996 cohort), 14 (1990), and 19 (1985) years old as judged from the principal pine seed crop that resulted in their regeneration; these were the ages used in the model.

An expression of stand growth was calculated by subtracting the stand-level property of subplots obtained during the first inventory from that obtained during the second inventory. Because some plots were measured during the early part of the 2005 growing season during the first inventory, the time interval is slightly less than two growing seasons. No compensation for measurement date was attempted because of the short-term nature of the monitoring period. We chose to present these interim results because the growth interval was fairly well balanced across treatments and ages.

RESULTS AND DISCUSSION

Stand Conditions in 2006

The precommercial thinning conducted in 2004 resulted in a visible change in stand conditions 2 years later (table 1). The most intensive thinning treatment reduced pine density to 12 percent of that in the unthinned control in the 1996 cohort, 16 percent in the 1990 cohort, and 26 percent in the 1985 cohort. Although cutting hardwoods was not an objective of the thinning operation, hardwoods were cut in the mechanical one- and two-pass mowing conducted in the 1996 cohort because of their presence on the mowed strips. In the selective chain-saw thinning, hardwoods were cut to gain access to treated pines, which were the real objective of the operation. Thus, hardwood densities were fairly variable 2 years after treatment, when hardwood density in the most heavily thinned treatments ranged from 14 to 54 percent of the unthinned controls. In the selectively thinned treatments, the residual pine density was generally higher than the specified target, because the treatments were done by contractors working across the entire area rather than by research technicians working on the plots. In addition, some residual stems were below the minimum threshold for treatment, but they were included in the monitoring procedure.

For the most part, the lowest pine basal areas occurred in the more heavily thinned stands; values for these treatments ranged from 24 to 50 percent of the untreated controls (table 1). Pine basal area in the unthinned controls was 62, 143, and 144 square feet per acre for the 1996, 1990, and 1985 cohorts, respectively. The peaking of basal area at slightly over 140 square feet per acre suggested that the carrying capacity of the site was attained after 16 years. As this relationship suggests, reduced growth and increased mortality characterized stand dynamics as the carrying capacity was approached. Pine basal area in the 1980 cohort, which was commercially thinned after 19 years, was within 16 percent of the carrying capacity of the stand, suggesting that another thinning is in order. Hardwood basal area was considerably more variable than that for the pines. In fact, the most heavily thinned treatment in the 1990 cohort actually exceeded the basal area of the control by 4 square feet per acre; this reflected the fact that thinning hardwoods was not a treatment objective.

Mean pine d.b.h. generally declined as residual pine density increased (table 1). Mean d.b.h. in the most heavily thinned treatment was 2.1, 1.3, and 1.4 times greater than that of the untreated control in the 1996, 1990, and 1985 cohorts, respectively. This difference reflected the increased diameter growth associated with the lower densities resulting from thinning. In addition, some "jump" in mean d.b.h. occurred in the selectively thinned treatments because the larger, more dominant trees were retained as crop trees. The commercially thinned 1980 cohort was only 0.6 inches larger in mean d.b.h. than the untreated control in the 1985 cohort. Hardwoods in the study area were considerably smaller on average than the pines and also were considerably more variable in mean d.b.h. across the precommercial thinning treatments.

A Preliminary Look at Stand Dynamics

The two inventories conducted in our study allowed capturing some summary information on stand dynamics. Because the first inventory on about half of the plots was conducted during the early part of the growing season, the time-basis of this comparison can at best only be expressed as about 2 years. However, comparisons among treatments were valid because the timing of the first measurement was fairly well balanced across treatments.

Pine mortality was strongly affected by stand age and residual pine density, with the unthinned controls displaying the highest rates (table 2). There was relatively little mortality occurring on any treatments that were precommercially thinned at any age. The annual number of dying pines averaged 0.8 percent of initial density for the precommercially thinned treatments over all three stand ages. The number of dying pines in the control declined sharply with increasing stand age—from 653 trees per acre in the 1996 cohort to only 70 trees per acre in the 1985 cohort. However, when expressed as a percentage of the initial pine density, the annual rate was fairly uniform across the three ages and averaged 7 percent. By comparison, the pine density mortality rate in the commercially thinned stands in the 1980 cohort was 2.6 percent per year. In terms of pine basal area, the precommercially thinned treatments lost an average of 0.1 square feet per acre annually, while the unthinned controls increased from 2 square feet/acre in the 1996 cohort to 7 square feet per acre in the 1985 cohort. Most of this mortality was in the smaller trees because the d.b.h. ratio for dying to living pines ranged from 0.3 to 0.9 across all ages and treatments. Hardwoods displayed similar patterns of mortality as the pines, except that rates were generally lower for both density and basal area.

For pine density, the mortality rates observed for the precommercially thinned plots and the commercially thinned stand were comparable to the 2 percent annual mortality reported for loblolly pine plantations by Zeide and Zang (2006) and the 2 percent average mortality rate observed in managed uneven-aged loblolly pine stands by Murphy and Shelton (1998).

Table 1—Means and associated standard error for each mean for stand properties after the 2006 growing season in naturally regenerated pine stands that were commercially thinned, precommercially thinned 2 years earlier to different densities, or unthinned controls

	Density		Basal area		d.b.h.	
Cohort and treatment[a]	Mean	Std. error	Mean	Std. error	Mean	Std. error
	trees/acre		*ft^2/acre*		*inches*	
	Pines					
1996:200	447	62	31.0	4.3	3.5	0.47
Two pass	1,043	211	27.6	5.1	2.1	0.09
One pass	2,425	330	54.1	5.7	1.9	0.07
Control	3,618	779	62.3	12.0	1.7	0.07
1990:100	290	44	33.9	3.0	4.6	0.47
200	273	25	42.7	4.1	5.2	0.33
400	343	38	48.5	8.2	4.7	0.32
Control	1,780	145	143.2	10.9	3.6	0.09
1985:100	140	11	65.8	7.0	9.1	0.29
200	215	22	89.6	7.2	8.7	0.28
400	265	15	105.1	5.9	8.4	0.15
Control	535	56	144.2	12.3	6.7	0.30
1980: Commercial	368	30	120.7	11.9	7.3	0.36
	Hardwoods					
1996:200	457	383	7.1	5.5	1.4	0.13
Two pass	805	171	17.0	2.8	1.8	0.10
One pass	740	57	18.5	2.6	1.8	0.07
Control	1,858	124	28.4	3.4	1.4	0.04
1990:100	218	112	14.2	5.6	3.3	0.67
200	273	147	7.5	3.2	2.2	0.68
400	75	53	7.1	4.5	4.0	1.23
Control	405	142	9.9	2.1	2.2	0.23
1985:100	30	17	1.5	1.1	2.5	0.99
200	45	33	2.7	2.5	2.4	0.83
400	15	15	3.5	3.5	6.3	-----[b]
Control	218	93	7.5	2.1	2.6	0.24
1980: Commercial	150	34	8.1	3.1	2.6	0.20

[a]Treatments: 100, 200, and 400=precommercially thinned using chain saws in 2004 to an operational target of 100, 200, or 400 pine trees/acre, respectively; one pass=6-foot strip mowed leaving a 2-foot strip; two pass=as in one pass except two mowed strips at right angles; Control=no treatment; Commercial=commercially thinned in 1999 to 200 crop trees/acre.

[b]Only one of the eight plots had hardwoods present.

Table 2—Mortality occurring over an observation period of about 2 years in naturally regenerated pine stands that were commercially thinned, precommercially thinned 2 years earlier to different densities, or unthinned controls

	Pines			Hardwoods		
Cohort and treatment[a]	Density	Basal area	d.b.h. ratio[b]	Density	Basal area	d.b.h. ratio
	trees/acre	*ft²/acre*		*trees/acre*	*ft²/acre*	
1996:200	10	0.0	0.30	40	0.2	0.65
Two pass	8	0.1	0.92	18	0.1	0.68
One pass	68	0.5	0.68	25	0.2	0.70
Control	653	2.1	0.54	118	0.5	0.70
1990:100	15	0.4	0.63	0	0.0	-----[c]
200	5	0.4	0.78	5	0.0	0.15
400	5	0.2	0.59	0	0.0	-----
Control	288	6.2	0.60	53	0.4	0.57
1985:100	0	0.0	-----	5	0.2	0.90
200	0	0.0	-----	0	0.0	-----
400	0	0.0	-----	0	0.0	-----
Control	70	7.1	0.67	45	0.7	0.70
1980: Commercial	20	1.2	0.46	58	0.6	0.59

[a] Treatments: 100, 200, and 400=precommercially thinned using chain saws in 2004 to an operational target of 100, 200, or 400 pine trees/acre, respectively; one pass=6-foot strip mowed leaving a 2-foot strip; two pass=as in one pass except two mowed strips at right angles; Control=no treatment; Commercial=commercially thinned in 1999 to 200 crop trees/acre.

[b] Ratio of the d.b.h. of dying trees to the stand mean at the beginning of observation period.

[c] No trees present for analysis.

in the 1990 cohort and only 1.4 times in the 1985 cohort. In contrast, the change in stand basal area was greatest for the moderate densities, because more trees occupied the site which tended to compensate for the lower rates of d.b.h. growth. Plus, these moderate densities also had comparatively low mortality rates. The low level of net basal area change for the unthinned control in the 1985 cohort reflected the high rates of basal area loss associated with mortality. Also noteworthy was the low rates of hardwood d.b.h. growth and basal area growth when compared to the pines (table 3).

Individual Tree Growth

Annual basal area growth of individual trees was modeled from the d.b.h. of the tree and stand level properties, which were obtained from the subplot that the subject tree occurred on. A correction factor was also included to account for the difference in the initial start of the monitoring period. The pine prediction equation was:

$$\Delta B_p = \frac{29.16\left[1 - \exp\left(-0.1236 B_t\right)\right]}{1 + \exp\left(0.0003468P + 0.0001787H + 0.1868A + 0.2642M\right)} \quad (1)$$

where:

change in tree basal area in square feet from the first (2004 or early 2005) to second (2006) measurement divided by 2,

B_t = tree basal area in square feet at first measurement,
P = pine density at first measurement in trees/acre,
H = hardwood density at first measurement in trees/acre,
A = stand age in years at first measurement
M = indicator variable for timing of first measurement: 0=2004/05 dormant season, 1=2005 early growing season.

There were 4,070 observations for equation 1, the root mean square error was 0.00499 square feet, the coefficient of determination was 0.80, and all coefficients of treatment variables were significant at $P < 0.001$. A similar prediction equation was developed for hardwood basal area growth as follows:

$$\Delta B_p = \frac{29.16\left[1 - \exp\left(-0.1236 B_t\right)\right]}{1 + \exp\left(0.0003468P + 0.0001787H + 0.1868A + 0.2642M\right)} \quad (2)$$

Table 3—Change in mean stand d.b.h. and basal area occurring over an observation period of about 2 years in naturally regenerated pine stands that were commercially thinned, precommercially thinned to different densities, or unthinned controls

Cohort and treatment[a]	Pines		Hardwoods	
	d.b.h.	Basal area	d.b.h.	Basal area
	inches	*ft²/ acre*	*inches*	*ft²/ acre*
1996:200	1.05[b]	16.0	0.10	1.7
Two pass	0.55	13.0	0.34	5.5
One pass	0.38	18.5	0.20	4.0
Control	0.35	14.3	0.18	5.9
1990:100	0.79	9.8	0.14	1.4
200	0.74	11.5	0.18	1.1
400	0.66	13.1	0.26	0.6
Control	0.40	12.5	0.22	0.6
1985:100	0.89	12.0	-----[c]	----
200	0.66	12.8	0.16	0.6
400	0.63	16.1	0.28	0.3
Control	0.62	5.3	0.15	0.0
1980: Commercial	0.67	16.4	0.33	1.5

[a]Treatments: 100, 200, and 400=precommercially thinned using chain saws in 2004 to an operational target of 100, 200, or 400 pine trees/acre, respectively; one pass=6-foot strip mowed leaving a 2-foot strip; two pass=as in one pass except two mowed strips at right angles; Control=no treatment; Commercial=commercially thinned in 1999 to 200 crop trees/acre.
[b] Stand mean in 2006 minus that observed at beginning of monitoring.
[c] Inadequate number of trees for analysis.

Stand growth was also strongly related to precommercial thinning treatment and stand age (table 3). The change in mean pine d.b.h. was consistently greatest for the lowest residual pine density. In addition, the steepness of this relationship tended to decline through time; for example, the d.b.h. growth rate in the lowest density was 3.0 times that of the unthinned control in the 1996 cohort, but was 2.0 times where:

ΔB_h = change in hardwood tree basal area growth and all other variables are as previously defined. Equation 2 was based on 1,648 observations, the root mean square error was 0.0028 square feet, the coefficient of determination was 0.64, and all coefficients were significant at $P \leq 0.01$.

Solving equation 1 for a reasonable range of values for independent variables yielded the predicted values for pine basal area growth shown in figure 1. Growth progressed in a logical manner; increases occurred with increasing tree d.b.h. and decreases occurred with increasing pine density. The effects of stand age must be considered concomitantly with tree d.b.h., because tree d.b.h. varied considerably over the 11-year period covered by the model. The largest trees produced a relatively uniform annual basal area growth of 0.05 to 0.07 square feet over the range of stand ages represented by our study, which suggests that more rapid diameter growth of the dominant trees in the cohort will result when the cohort is precommercially thinned at an earlier age. The broadest range in basal area growth within the population was expressed at the younger ages before self-thinning substantially reduced stand density; this range changed from about 3 fold in the 1996 cohort to 1.4 fold in the 1985 cohort.

A similar relationship was developed from equation 2 for hardwoods (fig. 2). The similarity in hardwood d.b.h. range for each age probably reflected the different site preparation treatments used when the study areas were regenerated. The basal area growth pattern displayed for hardwoods substantially differed from that of pines. First, pines showed an increasing growth rate with d.b.h. throughout the range in diameters at each age, while hardwood growth became asymptotic for the larger diameters. Second, the growth rates for hardwoods were considerably below those for the pines. In the 1996 cohort, for example, the dominant hardwoods were growing at 0.03 to 0.04 square feet per year, which was only half the rate displayed by the dominant pines. In addition, hardwood growth rates decreased substantially through time, widening the growth differential between hardwoods and pines. This decline undoubtedly reflected the suppression of hardwoods by the rapidly developing pine component, which captured and dominated the site during early succession (Cain and Shelton 2001). Third, the expressed ranges in values for hardwood growth were much narrower than those displayed by pines.

CONCLUSIONS

Our study showed that controlling stand density through precommercial thinning strongly affected growth of individual trees and the patterns of stand dynamics. The lowest residual densities displayed the highest rates of individual tree growth. The effects of stand age on tree growth were minor for the dominant trees in the stand. At the stand level, however, moderate densities favored the highest levels of basal area growth, because more trees occupied the site and mortality was far lower than in the unthinned controls. Tree mortality through self-thinning was the driving force that caused the basal area growth of the stand to decline at the higher densities. Mortality was mainly from the smaller trees in the population. Results of our study reinforce the notion that the earlier precommercial thinning can be done, the better. In addition, stands are far easier to precommercially thin when the trees are smaller. Although the short-term results of this paper contribute to our knowledge of precommercial

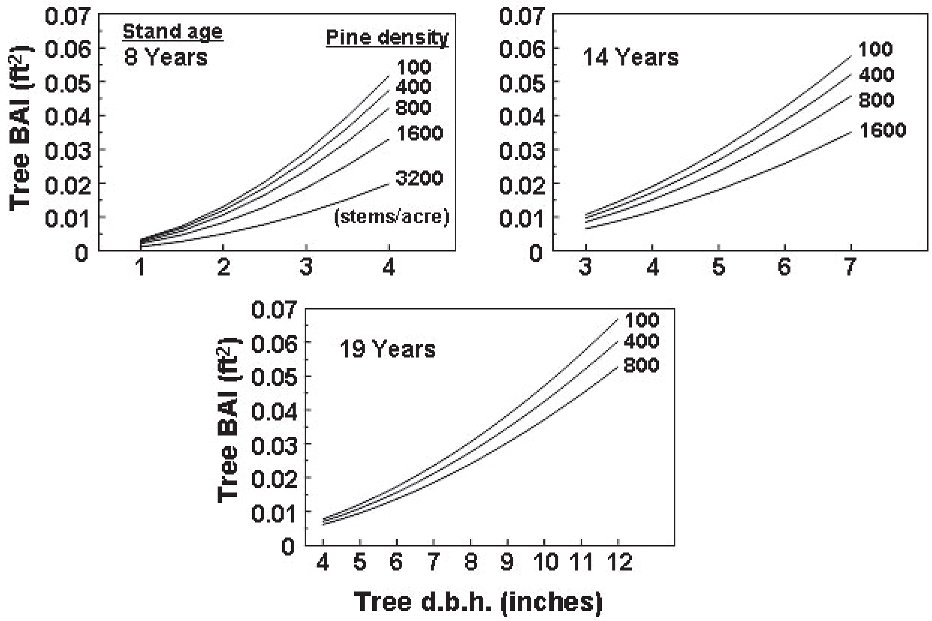

Figure 1—Annual basal area increment (BAI) of individual pines predicted from tree d.b.h., pine density, and stand age at treatment (2004) and for a uniform hardwood density of 500 trees per acre (equation 1 with $M = 0$).

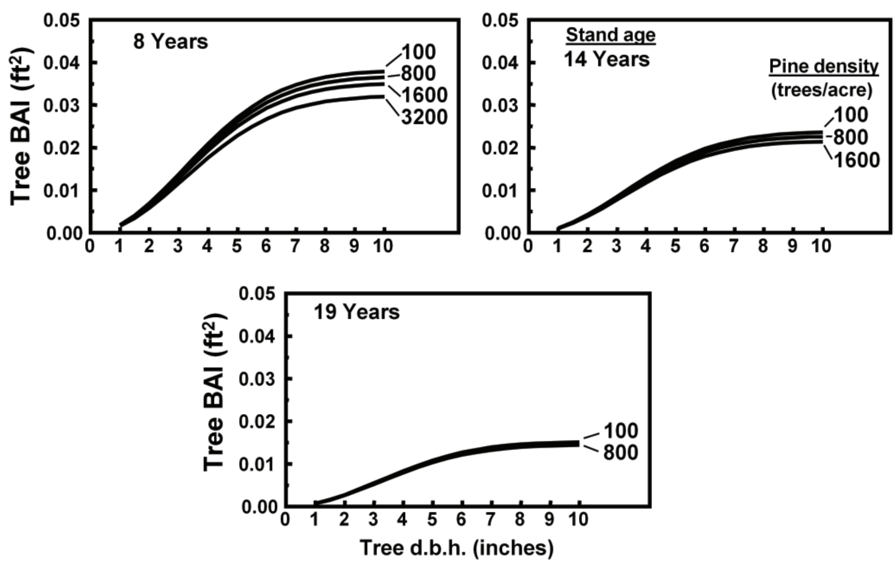

Figure 2—Annual basal area increment (BAI) of individual hardwoods predicted from tree d.b.h., pine density, and stand age at treatment (2004) and for a uniform hardwood density of 500 trees per acre (equation 2 with $M = 0$).

thinning, some issues, like economics, product yields, and tree quality, will have to wait for a longer monitoring period to resolve. This study also meets an important goal for science delivery in that we now have an active precommercial thinning demonstration on hand at the Crossett Experimental Forest for review by visitors, tour groups, short courses, and workshops.

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UNDERSTORY PLANT COMMUNITY RESPONSE TO COMPACTION AND HARVEST REMOVAL IN A LOBLOLLY PINE PLANTATION

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Abstract—In 1992 the Southern Research Station, U.S. Forest Service, constructed three Long-Term Soil Productivity (LTSP) installations in a loblolly pine (*Pinus taeda* L.) plantation on the Croatan National Forest in Craven County, NC. The LTSP study consists of a nationwide network of experiment sites designed to examine the long-term effects of soil disturbance on forest productivity, one aspect of which is the growth of understory vegetation. Each installation features three levels of soil compaction crossed with three levels of organic matter removal imposed on a harvested site prior to planting. Intensive surveys of the understory vegetation were carried out on the Croatan LTSP site prior to and two years after treatment installation, focusing on the extremes of the soil compaction (no compaction, severe compaction) and organic matter removal treatments (bole only, whole tree + forest floor). We collected plant community data in the summer of 2006 to address the following objectives: (1) to characterize the current standing understory vegetation, (2) to determine the interaction of organic matter removal and compaction treatments fourteen years post-treatment, and (3) to compare current vegetation patterns with the pre-treatment and two years post-treatment vegetation. Preliminary results of an analysis of variance of 2006 vascular plant richness data, as well as a description of changes in species composition over time, are presented here.

INTRODUCTION

The Long-Term Soil Productivity (LTSP) study was established by the U.S. Forest Service (USFS) in response to concerns about declining productivity in managed forests (Powers and others 1989, 2004). The first LTSP experimental site was installed in 1990 in LA. With the construction of additional experimental sites by the USFS in major forest regions across the United States, as well as the formation of partnerships within both the United States and Canada, the LTSP network has grown to include over 100 installations (Powers and others 2004).

The LTSP study focuses on two pulse disturbances associated with forest management activities that are likely to affect site productivity: reduction of soil porosity (through compaction) and removal of organic matter (Powers and others 1989, 2004). Soil compaction may hinder root growth as well as reduce the availability of oxygen, while organic matter removal is a concern because of the removal of nutrients from a site.

While the LTSP experiment was designed as a productivity study, the experimental framework provides an opportunity for studying the long-term effects of anthropogenic pulse disturbances on forest plant communities. The development of understory plant communities has implications for wildlife habitat, biodiversity, conservation of rare species, recreation, and non-timber forest products.

Studies of the long-term effects of organic matter removal set in North Carolina are particularly relevant as the woody biomass in the state's forests is being considered as a fuel source. As an example, North Carolina State University recently hosted a conference titled "Energy from Wood: Exploring the Issues and Impacts for North Carolina" (Raleigh, NC: March 13-14, 2006), to serve as a forum to discuss the issue. What are the long-term effects of removing more biomass during timber harvest on the development of forest plant communities? How would non-timber forest values and uses, such as biodiversity and wildlife habitat, be impacted by such a shift in harvest practices?

Objectives

This paper is a progress report on a study of the forest plant communities on an LTSP experiment site located on the Croatan National Forest in North Carolina. The objectives of the study are (1) to characterize the current standing understory vegetation at the Croatan National Forest LTSP site, (2) to determine the interaction of organic matter removal and soil compaction 14 years post-treatment, and (3) to compare current vegetation patterns with the pre-treatment and two years post-treatment vegetation. In other words, what vegetation patterns currently exist on the site? What patterns of changes have occurred over the years since timber harvest? Finally, are these patterns linked to the experimental treatment factors of soil compaction and organic matter removal?

METHODS

Study Site Description

The study area is an LTSP site located on the Croatan National Forest in Craven County, in the coastal plain of NC. The site lies in the extreme southeast portion of the county, near the intersection of State Highway 306 and Forest Route 132, roughly 2 km from the Neuse River. Goodwin (1989) characterizes the area's climate and soils; summers in Craven County are hot and humid while winters are cool with brief cold spells. July and August are the hottest months of the year, with average daily maximum temperatures approaching 32 °C; annual average temperature is 17 °C. Total annual precipitation is 138.4 cm, mostly falling from April through September. Ninety-nine percent of the land is nearly level or gently sloping to the southeast. Much of the county is poorly drained. Soils on the site are mapped as the Lynchburg series (fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults) and Goldsboro series (fine-loamy, siliceous, subactive, thermic Aquic Paleudults).

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Lankford (1995) reports that prior to timber harvest and the installation of the LTSP treatments the site supported a 65 year old loblolly pine (*Pinus taeda* L.) plantation with a component of mixed hardwoods in the mid and upper canopies. Woody shrubs were common in the understory. However, due to incomplete crown closure, a discontinuous herbaceous layer occurred throughout the site.

Experiment Design and Implementation

The LTSP experiment features a two-factorial randomized complete block design, with three levels of organic matter removal (bole only, whole tree, whole tree + forest floor) crossed with three levels of soil compaction (none, intermediate, severe) for nine total treatment combinations (Powers and others 1989). At the Croatan LTSP installations, each plot is further split into herbicide and non-herbicide treatments. Blocking is based on soil series. Block 1 is located on the Goldsboro series soil, while Blocks 2 and 3 are mapped as the Lynchburg series. Figure 1 contains a map of plot locations.

The existing timber on the site was harvested from July to September of 1991. Additional organic matter removal was carried out from October of 1991 through January 1992. Soil compaction treatments were implemented in December 1991 and March to April 1992. Loblolly pine seedlings were planted in April 1992 using 3 by 3 m spacing.

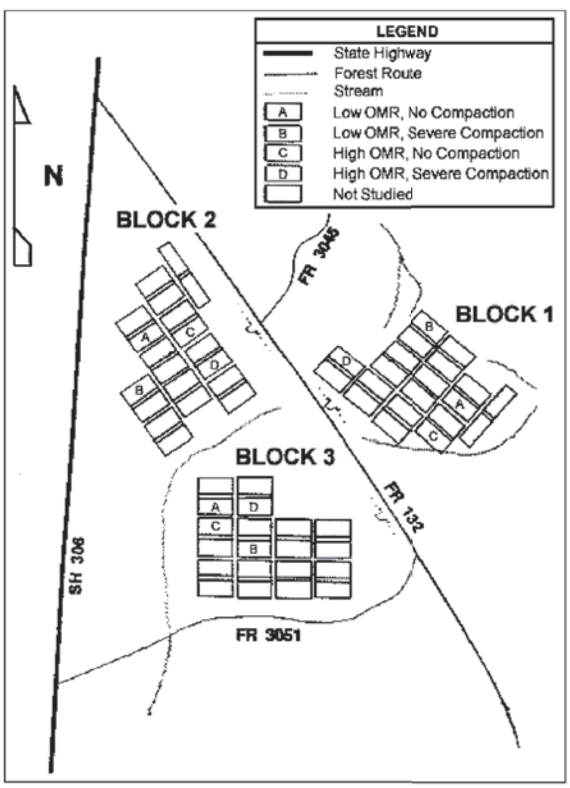

Figure 1—Map of the Croatan LTSP experiment site, showing plots studied.

This study is restricted to a subset of the non-herbicide treatment plots, including two levels of compaction (none and severe) and two levels of organic matter removal (bole only and whole tree + forest floor). This gives four treatment combinations for a total of twelve plots. The narrow focus was necessitated by budget and time constraints. However, the selection still allows for comparisons between the most extreme treatment levels and also preserves continuity with earlier vegetation surveys on the site, which focused on the same four treatment combinations.

Vegetation Survey

The plant communities on the site were surveyed from June through July of 2006 (14 years post-treatment) using the methodology developed by the Carolina Vegetation Survey (CVS) (Peet and others 1998). The preliminary results presented below are based on complete vascular plant species lists developed for the 20 by 50 m CVS sample unit nestled within each LTSP plot. Nomenclature follows Weakley (2006).

Previous vegetation surveys carried out on the Croatan LTSP site in 1991 (Lankford 1995) and 1993 (Mellin 1995) also followed the CVS protocol. The USFS Southern Research Station RWU-4154 (Forestry Sciences Laboratory, 3041 Cornwallis Road, Research Triangle Park, NC) shared the original data produced by these earlier vegetation surveys.

Initial Analyses

Vascular plant richness in 2006—Species richness, the number of species present in a given area, is a straightforward measurement of species diversity. Total vascular plant richness was determined for each plot and subjected to an analysis of variance (ANOVA) to test whether species diversity differed between plots based on the two treatment factors. The ANOVA was carried out using SAS software (SAS Institute 2001).

Changes in species composition—A descriptive approach was used initially to identify patterns of changes in species composition between study years (1991 to 1993 and 1993 to 2006) by treatment combination. The number of species gained and lost between study years on at least two of the three replications of each treatment combination was identified. These species were then grouped by growth form to identify patterns across categories of plants. Species were assigned to growth forms following the classifications used by the PLANTS Database (USDA Natural Resources Conservation Service [N.d.].

Due to the use of different taxonomic authorities, some plant species in the genera *Dichanthelium*, *Andropogon*, and *Rubus* were treated inconsistently between vegetation surveys. Species from these genera were abundant on the site during all three study years. Whenever necessary, species within these genera were lumped into broader groups to improve comparability between study years.

PRELIMINARY RESULTS

Vascular Plant Richness

In 2006 the Croatan LTSP site was a 14-year-old loblolly pine plantation that had experienced crown closure on all plots, with only infrequent small gaps in the canopy. 121 species of vascular plant were found there. The overall average vascular plant richness was 55.3 per plot. Adjusted for differences in the treatment of the genera *Dichanthelium*, *Andropogon*, and *Rubus,* the overall average richness in 2006 was 53.4 per plot, a slight decrease from 56.3 in 1991 (preharvest) and 56.8 in 1993 (two years post-harvest).

By treatment combination, average 2006 richness per plot was 51.3 for bole only organic matter removal without compaction, 52.3 for bole only organic matter removal with severe compaction, 57.7 for whole tree + forest floor organic matter removal without compaction, and 59.7 for whole tree + forest floor with severe compaction (fig 2). ANOVA revealed that the differences between the bole only and the whole tree + forest floor organic matter removal treatments were significant at $\alpha = 0.10$ level (table 1).

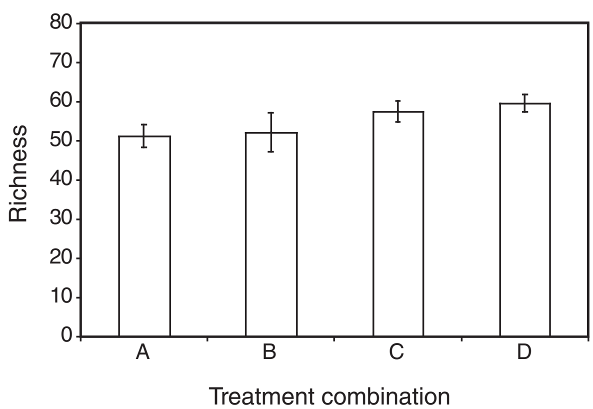

Figure 2—Vascular plant species richness in 2006, averaged by treatment combination, with standard error. A = bole only organic matter removal with no compaction, B = bole only organic matter removal with severe compaction, C = whole tree + forest floor organic matter removal with no compaction, and D = whole tree + forest floor organic matter removal with severe compaction.

Table 1—Results for ANOVA ($\alpha = 0.10$) performed on 2006 vascular plant richness data

Effects	P
Organic matter removal	0.063
Compaction	0.635
Interaction	0.873
Block	0.215
C.V. (%)	9.410
R^2	0.612

Changes in Species Composition

1991 to 1993—Between 1991 and 1993 the Croatan LTSP site was transformed from an established loblolly pine plantation with mixed hardwoods present in the mid- and upper-canopies (Lankford 1995) to an early-successional loblolly plantation. Figure 3a shows the species gained and lost between the two earlier vegetation surveys by growth form. Some of the patterns shown there simply reflect expected successional trends following removal of overstory plants; there was an influx of ruderal forbs/herbs and graminoids that commonly colonize disturbed areas. For example, the genera *Eupatorium*, *Solidago, Dichanthelium*, and *Rhynchospora* were represented by at least two species each. For each treatment combination the number of species gained was greater than the number lost, due to this influx of ruderal species.

One pattern may be linked to the intensity of the organic matter removal and soil compaction treatments; changes in species composition were most dramatic on the most intensive treatment combination (whole tree + forest floor and severe compaction), which at the same time gained the most (15) and lost the most (13) species. Also, the only losses of tree species—flowering dogwood (*Cornus florida* L.) and American holly (*Ilex opaca* Ait.)—occurred on this treatment combination.

1993 to 2006—Figure 3b shows species gained and lost from 1993 to 2006 by growth form. During this longer time period, the loblolly pine plantation on the study site experienced crown closure and the loss of many of the early-successional species gained between 1991 and 1993.

There is evidence for a soil compaction treatment effect: The severe compaction treatment combinations each lost more species than they gained, whereas the no compaction treatments gained roughly the same number of species as they lost. Curiously, the recruitment of vine species was particularly affected by compaction level. The two severe compaction treatments gained one species of vine each. In contrast, the no compaction treatments each gained four vine species, two of which—cross-vine (*Bignonia capreolata* L.) and Virginia creeper (*Parthenocissus quinquefolia* (L.)

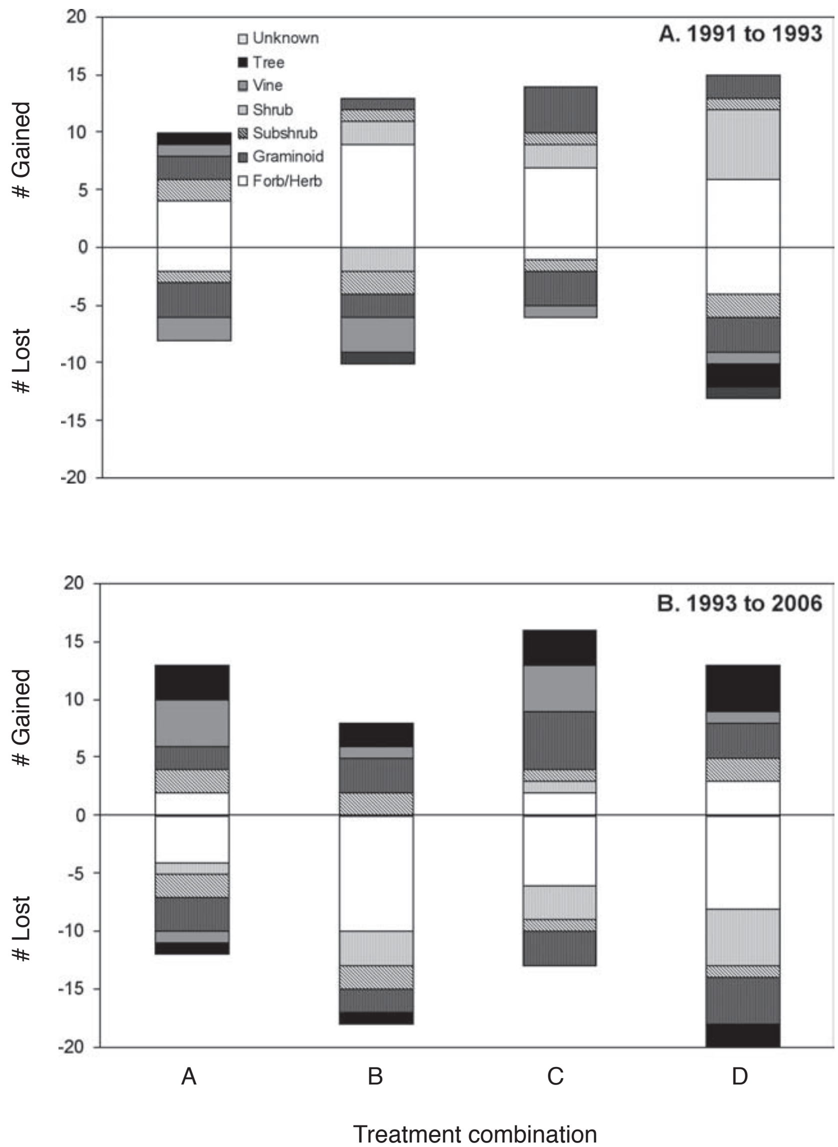

Figure 3—The number of vascular plant species lost and gained between study years on at least two of three plots for each treatment combination, by growth form. A = bole only organic matter removal with no compaction, B = bole only organic matter removal with severe compaction, C = whole tree + forest floor organic matter removal with no compaction, and D = whole tree + forest floor organic matter removal with severe compaction.

Planchon)—were gained on both of the no compaction treatments and neither of the severe compaction treatments. Coral honeysuckle (*Lonicera sempervirens* L.) was gained on both of the no compaction treatments, as well as the bole only organic matter removal and severe compaction treatment.

DISCUSSION

Initial Findings

The results presented here provide a partial account of the influence of organic matter removal and soil compaction on the development of plant communities on the Croatan LTSP site. In the short span of time from preharvest to early-successional conditions (1991 to 1993) the most intensive treatment combination (whole tree + forest floor and severe compaction) experienced the greatest changes in species composition; other treatment effects are unclear. From early-successional conditions to a few years after canopy closure (1993 to 2006) there is evidence that the soil compaction treatments influenced species compositional change, most notably that of vines. However, ANOVA of 2006 species richness revealed an organic matter removal effect, not a soil compaction effect, 14 years post-treatment. This potential disparity may simply reflect that ANOVA was only performed on the total number of species and not on differences by growth form. Alternatively, the changes in diversity due to soil compaction may have occurred outside of the 1993 to 2006 time frame.

Next Steps

The analyses presented here do not take full advantage of the rich dataset provided by the use of the CVS protocol (Peet and others 1998). In addition to the presence and richness data used above, the abundance of each species was recorded in terms of percent cover. Stems were tallied by species and by diameter class, providing both another measure of abundance and a means of evaluating the structural composition of the plant communities on the site.

Data analysis will be refined and continued through the use of multivariate techniques such as cluster analysis or indirect ordination, which can be used to evaluate the abundance data collected. The ANOVA of vascular plant richness will be expanded to include richness by growth form, in order to evaluate the effects of the experimental treatments on specific categories of plants. An ANOVA will also be performed on the stem count data to evaluate treatment effects on the density of stems. The descriptive evaluation of changes in species composition will be expanded to include the 1991 to 2006 time period, which would allow comparisons between current and preharvest species composition.

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A COMPARISON OF NORTHERN AND SOUTHERN TABLE MOUNTAIN PINE STANDS

Patrick H. Brose, Thomas A. Waldrop, Helen H. Mohr[1]

Abstract—Table Mountain pine (*Pinus pungens*) stands occur throughout the Appalachian Mountains, but ecological research has concentrated on the southern part of this region. In 2006, research was initiated in northern Table Mountain pine stands growing in PA to compare some basic attributes of those stands with previously described ones in TN. Overall, the northern and southern stands were quite similar. Both contained 13 species, 10 of which they had in common. In the overstory, the PA stands had fewer trees, fewer pines, more oaks (*Quercus* spp.), and less basal area per acre than the TN stands. The PA stands also had Table Mountain pines with nonserotinous cones while those in TN had sealed cones. In the understory, the TN stands had more shrub cover, taller shrubs, and much less pine regeneration per acre than the PA stands. The presence of pine regeneration in PA and its absence from TN are likely due to the differences in cone type and shrub cover.

INTRODUCTION

Mountain pine (*Pinus pungens*) is a native hard pine of the Eastern United States. It, along with pitch pine (*P. rigida*), shortleaf pine (*P. echinata*), and Virginia pine (*P. virginiana*), forms small scattered stands throughout the Appalachian Mountains. Table Mountain pine (TMP) stands occur from southern PA to northern GA on thin, dry soils of south- and west-facing ridges and upper slopes between 1 000 and 4 000 feet (Della-Bianca 1990, Williams 1998, Zobel 1969). TMP stands are becoming increasingly valued for diversity by land managers because they constitute an uncommon conifer community in an otherwise hardwood-dominated forest landscape.

Because of this intrinsic diversity value, TMP stands have been rather extensively studied by forest ecologists over the past 15 to 20 years. Before 1990, only eight papers were published and four were authored by the same individual (Barden 1977, 1979, 1988; Barden and Woods 1974). Since 1990, publications on TMP stands have nearly quadrupled to 30 papers; however, virtually all of this research has been conducted in the southern Appalachian Mountains. TMP stands in the northern part of its range have been virtually ignored. The only research focused on northern TMP stands was that by McIntyre (1929) and Zobel (1969). The former studied cone and seed production and the latter included five TMP stands from PA in his monograph on the ecology of the species.

In 2006, an opportunity arose to complete a dendroecology study started in 1991 of three TMP stands in southern PA (the northern end of Table Mountain pine's range). In this paper, we compare the characteristics of those stands (PA) to TMP stands growing at the southern end of the species range in eastern Tennessee (TN).

METHODS

Study Sites

Two of the three northern TMP stands were on Mont Alto Mountain in the Michaux State Forest and the other was on Martin Hill in Buchanan State Forest. All three of the southern TMP stands were on Gregory Ridge in Great Smoky Mountains National Park. All of the TMP stands occurred on the top and upper slopes of north-south oriented ridges. The PA stands were primarily on the west side of the ridges with azimuths ranging from 220 to 290 degrees while the TN stands were on east aspects (azimuths from 90 to 120 degrees). All stands were rocky and steep; slope sometimes exceeded 50 percent. The PA stands ranged in elevation from 1 500 to 1 900 feet a.s.l. while those in TN were about twice as high above sea level (2 880 to 3 540 feet). Soils in all stands were sandy loams that formed in place by the weathering of gneiss, sandstone, and schist parent material (Davis 1993, Knight 1998, Long 1975). Consequently, soils were of low fertility and strongly acidic. All stands appeared to have been undisturbed for decades and were composed of TMP, one or more other pine species, several hardwoods (especially chestnut oak (*Quercus montana*)), and various ericaceous shrubs.

In 1999, in each southern TMP stand, fifteen 0.05-acre (33 by 66 feet) rectangular plots were systematically established to uniformly cover the area as part of a landscape-scale TMP dendroecology project (Brose and Waldrop 2006). In 1991, in the three northern TMP stands, a total of 60 to 65 dominant Table Mountain pines were selected and tagged for use in a dendroecology study. This project was never completed and those stands and tagged trees were relocated in 2006. Two stands still existed and 15 tagged pines were randomly selected in each one, and a 0.05-acre circular plot was established with the tagged tree at the center. The other PA stand no longer existed so a nearby TMP stand was selected as its replacement based on similarity in appearance to the other two PA stands. In this stand, we systematically selected 15 dominant TMPs to uniformly cover the area and established a 0.05-acre circular plot around each of these dominant TMPs.

In each plot, all trees more than 10 feet tall were identified to species, counted, and measured to the nearest inch in diameter at breast height (d.b.h.). These data were subsequently used to calculate importance values for each species (Cottam and Curtis 1956). Pine seedlings and saplings less than 10 feet tall were also tallied throughout the

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entire plot into one of three height classes: less than 2 feet, 2 to 5 feet, and more than 5 feet. We estimated percent cover of evergreen shrubs, almost exclusively mountain laurel (*Kalmia latifolia*), for the entire plot by standing in the center and visually grouping all shrubs together (Marquis and others 1992). Shrub height was measured to the nearest half-foot on one shrub visually judged to be the average height of all shrubs present on the plot. Slope and aspect were also determined from plot center and recorded to the nearest degree and azimuth.

Our null hypotheses were that no differences existed between the PA and TN sites in any of the plot-level response variables, i.e., basal area, trees per acre, seedling and sapling density, shrub cover and height, etc. Each of these was compared between the PA and TN sites using t-tests with separate variances (SAS 2002). To ensure the assumptions of independence and normal distribution were met, the data from the stands in each respective state were pooled. This increased sample size to 45 for each state and limited the effect of any intrastand relationship due to two or more of the individual stands having a shared developmental history.

RESULTS

The PA and TN sites had numerous tree species in common (Table 1). Thirteen tree species were found at each site and ten of these occurred at both sites. Species common to PA and TN were: Table Mountain pine, pitch pine, chestnut oak, scarlet oak (*Q. coccinea*), white oak (*Q. alba*), red maple (*Acer rubrum*), blackgum (*Nyssa sylvatica*), American chestnut (*Castanea dentata*), serviceberry (*Amelanchier* spp.), and pignut hickory (*Carya glabra*). Black oak (*Q. velutina*), flowering dogwood (*Cornus florida*), and sourwood (*Oxydendrum arboreum*) were found only in the TN stands while eastern white pine (*P. strobus*), sweet birch (*Betula lenta*), and eastern hemlock (*Tsuga canadensis*) were present only in the PA stands.

Table Mountain pine was the most important conifer at both sites with importance value (IV) scores of 27 for PA and 31 for TN (table 1). These relatively high IV scores were the result of this species' abundance, size, and stocking. TMP densities were 78 and 161 trees per acre for PA and TN, respectively. This species also had the most basal area with an average of 58 square feet per acre for PA and 78 square feet per acre for TN. Table Mountain pine was quite widespread at both sites; occurring in all 45 plots in PA and 40 of 45 plots in TN. Pitch pine was the only other conifer common to both sites and was an important species in Tennessee (IV = 19) where it averaged 99 trees per acre, 38 square feet per acre of basal area and was found in 37 of the 45 plots. Pitch pine was not nearly as important in PA where its abundance, dominance, and stocking were 7 trees per acre, 4 square feet per acre of basal area, and 17 of 45 plots, respectively, gave it an importance value of 5.

Chestnut oak was the most important tree species in PA with an importance value of 29 (Table 1). In PA, chestnut oak averaged 103 trees per acre, 60 square feet per acre of basal area, and occurred on 41 of 45 plots. Scarlet oak was the second most important hardwood in PA's TMP stands (IV = 17). It was quite abundant and widespread, 88 trees per acre and 38 of 45 plots, respectively, but lacked in dominance with an average basal area of 14 square feet per acre. Chestnut oak also was the most important hardwood in the TMP stands in TN. There it averaged 47 trees per acre, 22 square feet per acre of basal area, and was found on 33 of 45 plots. These characteristics gave chestnut oak an importance value of 12, making it the third most important species overall—well behind Table Mountain and pitch pine. Red maple was a close second in importance (IV = 11) to chestnut oak in the TN stands because it had slightly fewer trees per acres and occurred on slightly fewer plots.

Between the two sites, all response variables were significantly different (Table 2). TN averaged more trees per acre, 435, and more basal area, 205 square feet per acre, than did PA which had 374 trees per acre and 151 square feet per acre. Mountain laurel covered an average of 54 percent of each plot in TN while mean cover in PA was less than half that amount. Average height of mountain laurel in TN was 8.1 feet, double the mean height of mountain laurel found in PA (4.0 feet). TMP regeneration also differed between the sites. In TN, regeneration of any pine species was virtually non-existent; less than five stems per acre and all less than 2 feet tall. In PA, density of TMP regeneration averaged 350 stems per acre and these were found in all size classes: 250 less than 2 feet tall, 75 between 2 and 5 feet tall, and 25 more than 5 feet tall. Although not quantified, it was observed that nearly all TMP cones in TN were sealed shut with resin (serotinous) regardless of how many years they had been on the branches but those in PA were nonserotinous and opened in the fall and winter to disperse the seeds.

DISCUSSION

At first glance, the TMP stands in PA and TN appear to have much in common. All occur on or near the top of steep rocky ridges. All stands have somewhat of a southerly aspect. In both states, pines dominate a discontinuous overstory and a mix of oaks and other hardwoods form the midstory. They share the same two major pine and hardwood species—Table Mountain pine and chestnut oak. They have eight associate species in common. Mountain laurel is found to varying degrees in all stands.

Despite their similarities, we detected significant differences in the overstory, shrub, and regeneration layers between the two states. The PA TMP stands are, in reality, oak-pine stands because they have considerably more oak than pine; the TN stands are the opposite: pine-oak stands with noticeably more pine than oak. This difference in composition is likely due to differences in their developmental history.

The PA stands are near old charcoal iron furnaces (Birkenbine 1894). During the 1800s, this industry completely clearcut forests on a 15 to 20 year cycle. Such an intense, frequent disturbance regime promotes species capable of resilient sprouting and precocial seed production. Chestnut oak has both traits (McQuilken 1990). Sprouting probability ranges from 50 to 100 percent depending on stem diameter and chestnut oak sprouts can produce abundant acorn crops by age 7 or 8. Many forests used by the charcoal iron industry were protected

Table 1—Tree species found in the Pennsylvania and Tennessee TMP stands and their abundance (trees per acre), dominance (ft²/ac of basal area), stocking (number of plots with at least one stem), and importance value (average of relative abundance, dominance, and stocking expressed as a percent)

Common Name	Abundance	Dominance	Stocking	Imp. Value
Pennsylvania				
Chestnut oak	103	60	41	29
Table Mountain pine	78	58	45	27
Scarlet oak	88	14	38	17
Red maple	47	3	25	9
Blackgum	24	4	22	7
Pitch pine	7	4	17	5
Eastern white pine	11	2	7	2
American chestnut	3	1	4	1
Pignut hickory	3	1	2	<1
Serviceberry	5	2	5	<1
Sweet birch	3	1	5	<1
White oak	5	2	3	<1
Eastern hemlock	3	1	6	<1
Totals	374	151	214	100
Tennessee				
Table Mountain pine	161	78	40	31
Pitch pine	99	38	37	19
Chestnut oak	47	22	33	12
Red maple	42	22	30	11
Scarlet oak	24	13	21	7
Sourwood	15	9	22	6
Blackgum	16	9	17	5
Black oak	16	9	9	3
Serviceberry	4	1	4	2
American chestnut	3	1	4	1
Pignut hickory	3	1	2	1
White oak	3	1	2	1
Flowering dogwood	2	<1	2	1
Totals	435	205	223	100

from fire and livestock grazing (Birkenbine 1894). Decades of this type of disturbance regime likely contributed to chestnut oak dominating these sites and making them oak-pine forests.

The TN stands were never logged but did experience frequent fire and livestock grazing due to their proximity to Cades Cove (Dunn 1988). Throughout the 1800s and early 1900s, farmers of this isolated community burned the surrounding forest to provide forage for their cattle and hogs. The stands were essentially wooded pastures until the 1920s. The hog feeding probably was especially critical to the lack of chestnut oak in the current stands. Hogs feed heavily on nuts in the autumn, and the large acorns of chestnut oak would have been a prime target. Few acorns probably survived to become seedlings. Those that did then had to withstand frequent surface fires and browsing by cattle, other livestock, and wildlife. When the burning and grazing regime abated in the late 1920s and early 1930s with the abandonment of Cades Cove, the growing space was captured by fast-growing pines resulting in the present pine–oak forest.

The TN stands had significantly more mountain laurel than the PA stands and the TN laurel was twice as tall. Not enough is known about the seedbed requirements of

Table 2—Attributes (mean ± one standard error) of the overstory, shrub, and regeneration layers at the Pennsylvania and Tennessee TMP stands. Small, medium, and large TMP seedlings are < 2 feet tall, 2 to 5 feet tall, and > 5 feet tall, respectively

Attribute	Pennsylvania	Tennessee
Overstory density (trees/acre)	374 ± 16	435 ± 21*
Overstory basal area (square feet/acre)	151 ± 11	205 ± 17*
Mountain laurel cover (percent)	23 ± 10	54 ± 18*
Mountain laurel height (feet)	4.0 ± 1.3	8.1 ± 1.5*
Small TMP density (seedlings/acre)	250 ± 108	4.3 ± 3.6*
Medium TMP density (seedlings/acre)	75 ± 39	0.0 ± 0.0*
Large TMP density (seedlings/acre)	25 ± 16	0.0 ± 0.0*
Serotinous cones present (yes/no)	No	Yes

* significant difference at the 0.05 level between states for that particular attribute.

mountain laurel to know if a fire/grazing regime would favor the shrub over a frequent cutting regime. The differences between states may be due to latitudinal and altitudinal variables because mountain laurel cover and height in TMP stands tend to increase from north to south and from low to high elevation (Zobel 1969, authors' pers. obs.).

Perhaps the most interesting difference between PA and TN TMP stands is the difference in pine seedling density and height. The PA stands had abundant Table Mountain pine regeneration of varying heights. Some stems were more than 10 feet tall. The three TN stands had only a few pine seedlings and they were always just a few inches tall.

This stark difference is likely due to two important factors: coverage of mountain laurel and serotiny of the Table Mountain pine cones. The TN stands had widespread, tall mountain laurel to the point that more than 50 percent of the stands were covered. Often, this shrub would be so dense it was nearly impossible to crawl through it. Additionally, the laurel was tall, averaging 8 feet in height. Consequently, these laurel thickets continually cast a dense shade on the forest floor and Table Mountain pine seedlings are intolerant of dense shade (Della-Bianca 1990). Additionally, the Table Mountain pine cones in TN were serotinous. Nearly all the cones for the past several years were still sealed shut with resin and attached to the branches. The TN stands suffered from limited seed fall and limited suitable seedbeds. Consequently, Table Mountain pine regeneration was virtually nonexistent.

The PA TMP stands did not have these same seed fall and seedbed limitations. Table Mountain pine in PA has nonserotinous cones; they open every fall to release their seeds. Consequently, there is a fairly regular seed fall and these seeds have a reasonable chance to find a suitable seed bed because the PA TMP stands also had much less mountain laurel. Coverage and height of this shrub was less than half that of TN and except for a few small areas, moving through the Pennsylvania stands was fairly easy. Where mountain laurel was dense in the PA stands, no pine regeneration was found.

Perpetuation of Table Mountain pine stands in either state requires active management. In TN, prescribed fire is probably the only reasonable method for perpetuating these TMP stands because they are in a national park (no logging and only restricted herbicide use) and the mountain laurel shrub layer is already dense enough to preclude regeneration. Burning of mountain laurel can be difficult due to its high flammability, but the intense fire readily kills the laurel, opens the sealed cones, and creates a suitable seedbed (Waldrop and Brose 1999). In PA, logging probably is a suitable approach because the cones open without fire and the laurel is still a minor obstacle to regeneration. The key will be to sufficiently disrupt the laurel shrub layer to prevent its spread and establish new pine seedlings.

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LONG-TERM AFFECTS OF A SINGLE P FERTILIZATION ON HEDLEY P POOLS IN A SOUTH CAROLINA LOBLOLLY PINE PLANTATION

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Abstract—While phosphorus (P) fertilization increases plant available or "labile" P immediately after fertilization, it is uncertain how it influences P pools over the long term in forest soils. Phosphorus pools from a 22-year-old loblolly pine (*Pinus taeda* L.) fertilization study were quantified using the Hedley sequential fractionation procedure, Mehlich-1, and Mehlich-3 soil tests. The Hedley fractionation procedure partitions the extracted P into six fractions, which are then defined as labile, moderately labile, and recalcitrant P pools. After 22 years, fertilization effects were limited to the surface horizon. The largest response to fertilization in this study was an increase in the Hedley recalcitrant P pools in the 0 to 10 cm soil horizon. Mehlich-3 extractable P was significantly ($p = 0.02$) larger in the 0 to 10 cm soil horizon of the fertilized treatment compared to the control. Our results suggest the largest portion of applied P has remained in the surface soil horizon and has the potential to increase site quality.

INTRODUCTION

Plant growth is typically limited by nitrogen (N) and P availability in forests soils. While the absolute quantities of these nutrients in forests soils may be large and appear sufficient to support robust plant growth in some locations, the actual pools of labile P are markedly smaller and typically growth limiting. The simple and economically viable solution in agriculture and plantation forestry operations has been to apply inorganic fertilizers to meet plant growth requirements. In 1999 nearly 500 000 ha of pine plantations in the Southeastern United States were fertilized with P or a combination of P with N (NCSFNC 2000). Whereas inorganic N can be volatilized and rapidly lost from the site after fertilization, the fate of inorganic P (Pi) and organic P (Po) is typically considered to be regulated by plants, soil microbes, and the P fixation capacity of the soil (Turner and Lambert 1988, Yuan and Lavkulich 1994).

The affects of P fertilization on the long-term P cycle in forest soils has recently been investigated in pine plantations in the Southeastern United States. Fertilization can increase plant uptake of P and the total P concentrations in litterfall up to 400 percent (Dalla-Tea and Jokela 1991, Piatek and Allen 2001). Several studies have shown that the O horizon may be a sink for P in forest soils due to an accumulation of P over time (Piatek and Allen 2001, Sanchez 2001). Comerford and others (2002) sampled plant and soil responses to a single P application of 17.5 kg-P/ha, 29 years after fertilization. Their results supported the view that P fertilization increased the pine needle litter P content, and increased labile pools P from easily mineralizable Po.

In the early 1980s a large number of silvicultural research trials were established to examine interactions among site preparation, weed control, and fertilization. The short- and medium-term growth response to a single P treatment of 56 kg/ha applied as 280 kg/ha DAP showed increases in stand growth in excess of 100 percent on many sites (NCSFNC 2004). Determining the fate of the applied P may elucidate the long-term affects of P fertilization on labile P pools. A significant and long-term increase in labile P pools may positively affect the following rotation's growth thereby reducing the need for increasingly expensive fertilizers applications and improving forest site quality.

There are a variety of methods to test for biologically available or "labile" P depending largely upon the physical and chemical properties of the soils you are testing (Pierzynski 2000). Routine soil tests such as Mehlich-1 (M-1), Melhich-3 (M-3), and Olsen-P use a variety of different chemicals to predict labile P pools (Tiessen and Moir 1993). The results of these tests are correlated with plant growth experiments that predict critical levels of P pools to meet agronomic crop needs. These equations typically account for 50 to 60 percent of the observed variability in crop growth (Tiessen and Moir 1993). While these empirically derived equations work well in agronomic crops they may be less reliable in forested ecosystems where biogeochemical cycling of P is more important and long rotation cycles limits their usefulness.

The Hedley sequential fractionation procedure attempts to quantify P pools within a soil by using a sequential chemical fractionation (Hedley and others 1982). The Hedley fractionation procedure has the advantage over most routine soil tests in its attempt to measure Po and Pi pools. These Po and Pi pools are then partitioned into labile, moderately labile, and recalcitrant P pools based upon to the chemical strength of the P bonds and the plants ability to access those P pools (Hedley and others. 1982, Tiessen and Moir 1993).

Our long-term goal is to have site specific, whole rotation, nutrient management recommendations for loblolly pine plantations. To attain this goal we need to understand the long-term effects of management practices on labile P pools. The specific objectives of this research project are to quantify the effects of fertilization on the Hedley P pools in loblolly pine plantation soils. Our hypotheses are that 20 years after fertilization:
Ha: Hedley labile P pools in the fertilized plots will be significantly greater than control plots.
Ha: Hedley moderately labile organic P pools in the fertilized plots will be significantly greater than control plots.

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MATERIALS AND METHODS

Field Experiment

Treatment plots sampled in this study were established in a loblolly pine plantation in Williamsburg Co., SC (SC1101). The SC1101 site was planted in March 1979 and fertilized with 56 kg-P/ha applied as 280 kg-DAP/ha in April 1979. All trials were installed with four blocks based on uniformity of soil and site conditions. Treatment plots were 20 by 20 meters, with 16 rows of 16 trees planted at 2.4 by 2.4 meter spacing. The internal 8 rows by 8 trees served as the measurement plots. The site is located on a Wahee soil series (Aeric Endoaquults) in the coastal plains physiographic province. A factorial combination of two levels each of site prep, fertilization, and vegetation control were applied. The eight treatments were applied in a split-plot design with site preparation assigned the whole plots treatments. The subplot treatments were fertilization and weed control. A description of treatment applications and soil horizons sampled for this study is listed in table 1.

P Pools Assessment

Soil samples were collected within the plots in 2001 using a 7.2-cm-inside-diameter probe. Phosphorus pools were extracted from the 0 to 10 and 10 to 20 cm depths. The samples were sieved (< 2 mm) to remove coarse debris, air dried, and stored in plastic bags until analyses. The soil samples within each plot were again passed through a 2 mm sieve and composite samples were analyzed for Hedley P content following the procedure of Tiessen and Moir (1993). Mehlich-1 and M-3 extractable P were also quantified (Pierzynski 2000). Subsamples of the composites were oven dried weigh and moisture corrections. Three lab replicates were analyzed per composite samples.

Hedley sequential fractionation—The Tiessen and Moir (1993) adaptation of the Hedley sequential fractionation procedure uses six extracting solution of differing ionic strength to divide the P content into pools of decreasing biological availability (fig. 1). The six sequential fractions are (1) deionized water with an anion exchange membrane-P; (2) $NaHCO_3$-Pi and -Po; (3) NaOH-Pi and -Po; (4) 1M HCl-P; (5) hot concentrated HCl-Pi and -Po; and (6) H_2SO_4/H_2O_2-Pi which when summed give Total Hedley P. Readers should refer to Tiessen and Moir (1993) for a detailed description of the fractionation procedure.

Methods of Analysis

Statistical analyses were performed using the MIXED model with restricted/residual maximum likelihood estimation method for a split-plot design in SAS software (SAS Institute, Cary, NC). The Satterthwaite option was employed to calculate the correct degrees of freedom. When necessary, data was natural log transformed, when appropriate, to meet the model assumptions. Generalized least squared means were calculated and analyzed for treatment effects at the $p < 0.05$

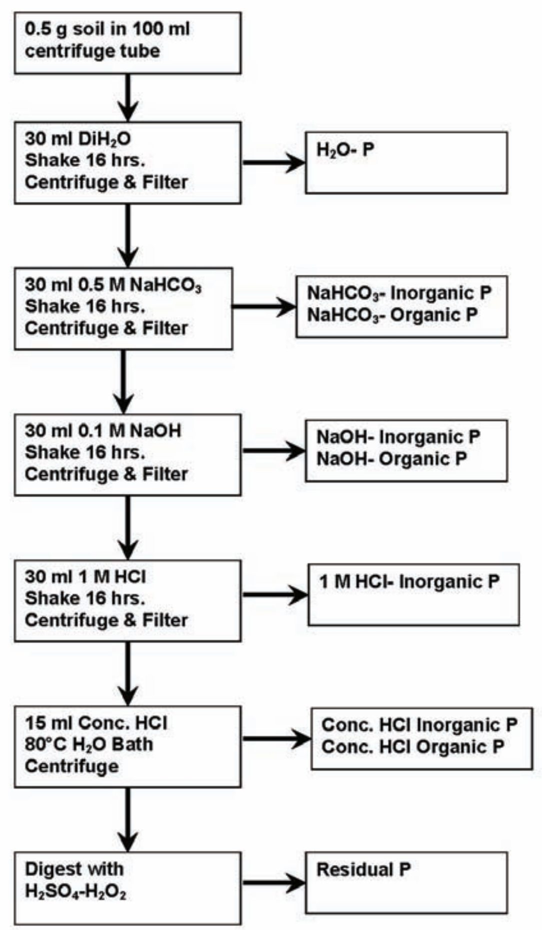

Figure 1—Schematic representation of the Tiessen and Moir (1993) modification of the Hedley sequential fractionation procedure.

RESULTS AND DISCUSSION

The Hedley labile P, Mehlich-1, and Mehlich-3 extractable P pools were largest in the surface horizon and fertilized treatment (table 2). Hedley labile P pools are slightly larger in the surface horizon of the fertilizer plots compared to the

Table 1—Silviculture treatments and soil depths sampled for quantification of Hedley P pools. Treatment chosen exhibited the largest growth response 14 years after fertilization a. i. = active ingredient

Treatment	Site Prep	Fertilizer (kg-P/ha)	Weed Control (kg-hexazinone/ha)	Soil Depth (cm)
Control	Chop	0	0	0 - 10
Fertilized	Chop, Bed	56	1.12	10 - 20

Table 2—Summary of Hedley P pools, Mehlich extractable P pools, from the 0-10 cm soil horizon of a SC loblolly pine plantation. Treatments were 0 or 56 kg/ha P applied at establishment. Values in parenthesis represent standard error of the means

Extraction	Treatment (P mg/kg)		Difference %	Contrast p-value
	Control	Fertilized		
Mehlich-1	5.3	7	32	*
Mehlich-3	49.4(1.16)	80.9 (1.16)	64	p = 0.005
Hedley Labile P	9.6 (0.71)	11.5 (0.28)	19	p = 0.096
Hedley Mod. Labile P	1.8 (1.3)	3.53 (1.3)	98	p = 0.059
Hedley Recalcitrant P	45.3 (4.8)	59.6 (4.9)	31	p = 0.039
Total Hedley P	56.8 (5.9)	74.7 (5.8)	31	p = 0.217

*Mehlich-1 was performed on a simple composite soil sample.

control plots ($p = 0.096$, table 2). This is supported by the increase in Mehlich-1 and Mehlich-3 extractable P pools in the fertilized plot (fig. 2). Both Mehlich-1 and Hedley labile P pools are measured by relatively mild extracting solutions which would be measuring P loosely sorbed to the mineral soil and Po compounds. Mehlich-3 extractable P was significantly higher ($p = 0.005$) in the fertilized treatments (table 2). Mehlich-3 uses a stronger extracting solution which, in comparisons to the Hedley fractions, appears to be liberating Pi from the more recalcitrant P pools (fig. 2).

Hedley labile P is extracted by the first two fractions (DiH_2O and $NaHCO_3$) and is readily absorbed by plants and microbes (Tiessen and Moir 1993). Anion exchange membranes first remove the Pi held in soil solution. The P extracted by the bicarbonate solution represents P that would be exchanged because of HCO_3^- generated from root respiration. These two pools of phosphorus are believed to represent the labile phosphorus pools (Cross and Schlesinger 1995, Johnson and others 2003, Tiessen and Moir 1993).

Hedley moderately labile P nearly doubled in the fertilizer treatment to 3.53 mg-P/kg-soil (table 2). While the increase confirmed our hypothesis, it makes up a very small portion of the extractable Hedley P (fig. 2). The Hedley moderately

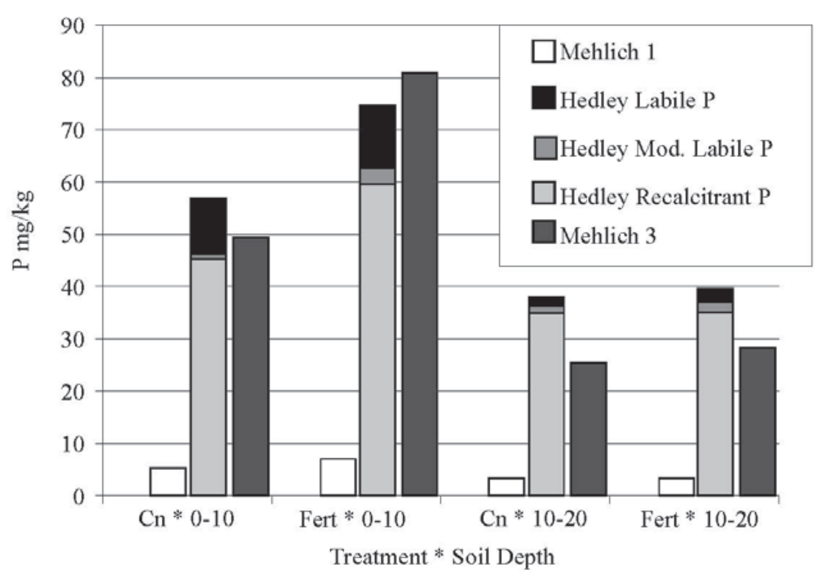

Figure 2—Mehlich-1, Mehlich-3, and Hedley extractable P pools from a SC loblolly pine plantation 22 years after a single fertilizer application of 280 kg/ha DAP. Treatments were 0 or 56 kg/ha P applied at establishment.

labile P pools are composed of the NaOH-Po and 1 M HCL fractions (Tiessen and Moir 1993). The NaOH-Po pool is believed to be involved in the long-term transformation of P pools but may be plant available over several years to decades. The Pi extracted from 1 M HCl is likely calcium associated Pi (Tiessen and Moir 1993). In acid forest soils it is likely generated in part from decomposing soil organic matter.

The Hedley recalcitrant P pool had the largest increased 22 years after fertilization to 59.6 mg-P/kg-soil (fig. 2). This was largely driven by an increase in NaOH extractable Pi ($p = 0.025$) and represent P bound to the Fe- and Al- oxides. When Pi is brought into soil solution, it is an anion that can be rapidly and strongly adsorb to soil Fe- and Al- oxides. The Pi anion can also be rapidly immobilized by plants or soil microbes. Therefore changes in Hedley P pools do not necessarily follow a sequential order. For example labile P may not be converted to moderately labile P which would in turn be converted to recalcitrant P.

The Hedley recalcitrant P pools include the 0.1 M NaOH-Pi, hot concentrated HCl, and the concentrated H_2SO_4/H_2O_2 fractionations (Cross and Schlesinger 1995). The P pools extracted by these solutions are believed to be highly recalcitrant and thought to be unavailable to the plant. However recent studies have shown changes in these pools attributed to plant or microbial uptake (Gahoonia and others 2000, Liu and others 2004, Liu and others 2006). These recalcitrant P pools may be made labile with the exudation of organic acids like oxalate from plant roots and soil microbes. These organic acids can release P from the Hedley recalcitrant P pools by increasing the solubility of P in the soil solution (Fox and Comerford 1992).

CONCLUSION

The Hedley fractionation procedure attempts to extracts P, based upon chemical solubility, into pools believed to have biological relevance. However, recent research has shown moderately labile and recalcitrant P pools are indeed accessible to the soil biota. Therefore interpretation of Hedley extractable P pools have been further complicated. Twenty-two years after fertilization all three soil tests showed an increased in labile P pools in the surface (0-10 cm) soil horizon. There was also a small increase in the Hedley moderately labile P pools. However, the fertilizer applied has been largely sequestered in the Hedley recalcitrant P pool. The increase was largely Pi associated with Fe- and Al-oxides. In light of recent research this does not preclude the potential that a portion of this P pool may be plant available for the following rotation.

Future research should be directed towards quantifying the long-term affects of fertilization on organic P species present using NMR. Additional research could monitor changes in Hedley P pools after harvesting operations.

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EFFECT OF BIOSOLIDS ON A LOBLOLLY PINE PLANTATION FOREST IN THE VIRGINIA PIEDMONT

Eduardo C. Arellano and Thomas R. Fox[1]

Abstract—Forests in the piedmont of VA may be a good alternative location for land application of biosolids. The objectives of this study were to quantify nutrient availability and tree growth in a loblolly pine (*Pinus taeda* L.) plantation following the application of different biosolids types, at different rates, and at two different times. The study was installed in September 2005, in a thinned loblolly pine plantation, located in Amelia County in the piedmont of VA. The study was established as a randomized complete block design with nine treatments. The treatments are three different biosolids types (lime stabilized, anaerobic digested, and pelletized), conventional fertilizer (Urea + diammonium phosphate), and seasonal applications (fall or winter). Biosolids increased soil nitrogen (N) availability and tree growth one growing season after application compared to the control treatment. Results for this study indicate that biosolids may be a good alternative to fertilizers to increase forest growth while providing additional sites for the land application of biosolids.

INTRODUCTION

Biosolids are solid or liquid materials produced during the treatment of sewage that has been sufficiently processed to allow land application of these materials (Evanylo 1999a). Approximately 5.6 million dry tons of sewage sludge are disposed of annually in the United States with approximately 60 percent used for land application (NRC 2002).

Land applications of biosolids are regulated by the US Environmental Protection Agency (EPA 2000). The EPA established regulations for the land application of biosolids, based on concentration limits and loading rates for specific chemicals. The EPA regulations are also designed to control and reduce pathogens or disease vectors.

Decreasing availability of agricultural land suitable for biosolids application in eastern VA due to urban expansion in the Washington-Richmond-Norfolk corridor may limit ongoing land application programs. Forestland in the Piedmont and Upper Coastal Plain of VA provides an alterative location for the land application of biosolids. In VA, approximately 50 percent (75 000 dry tons) of the biosolids produced annually by water treatment plants in the state are land applied (UVA 1997). In VA, the acreage permitted for biosolids land application represented approximately 2.5 percent of the 8 million acres in agricultural production in 1997 (UVA 1997).

Managed pine forests tend to grow on nutrient deficient soils and may be an effective nutrient sink. Growth of loblolly pine increases on most soils following fertilization (Fox and others 2007). In the South, the average growth response following fertilization with 200 pounds per acre of N and 25 pounds per acre of phosphorus (P) averaged around 55 cubic feet per acre per year. Similar to agricultural systems, biosolids supply plant essential nutrients that are deficient in most forest ecosystems, particularly N and P. Land application of biosolids can improve site productivity by increasing soil organic matter content. Because of the different organic forms found in biosolids, they function as slow-release fertilizers, releasing plant essential nutrients over time to the trees and crops (Evanylo 1999b). Published research shows that land application of treated municipal and industrial wastewater on forestland has been utilized successfully as source of nutrients at various locations in the United States for over 30 years (Cole and others 1986). A significant growth response frequently occurs in forests following the application of biosolids (Chapman-King and others 1986), but the growth response following biosolids applications to loblolly pine forests has been inconsistent. For example, McKee and others (1986) showed that liquid, not solid, biosolid applications increased tree growth in loblolly pine plantations. However, in young plantations, the increased competition from weeds whose growth was stimulated by the sludge application detrimentally affected the growth of the pine trees.

To ensure the sustainable application of biosolids to forested lands, we need to consider: (i) the ability of the soil to assimilate and cycle N; (ii) the cumulative effects of nutrients on the soil; and (iii) the change in bioavailability of nutrient with time. When properly managed, application of biosolids can increase tree growth due to increased mineral nutrient availability (Henry and others 1993, Kimberley and others 2002). Most of N in biosolids is organically bound N. The organic N needs to be mineralized before it becomes available for roots uptake. N mineralization of biosolids varies by sources (Kelty and others 2004), rates (Harrison and others 2002) and locations (Wang 2004). To avoid residual N, it is important to match the ability of the ecosystem to assimilate N mineralization rates. It has been reported that high application rates of biosolids could result in NO_3^- leaching from the site (Burton and others 1990). This study is a part of a larger project focusing on the effect of biosolids on nutrient cycling and tree growth. The objective of this study is to: (1) document the growth response of loblolly pine following the application of biosolids; (2) compare the growth response of loblolly pine to different types of commonly produced biosolids and conventional inorganic fertilizers; and (3) compare impact of biosolids application on N availability.

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MATERIALS AND METHODS

Study Area

The study was established in the summer of 2005 and it was conducted in Amelia County northeast of Blackstone, VA. The site supports a loblolly pine plantation that is 18-years old. The stand was thinned in 2004-2005 using a combination of fifth-row removal and low thinning between the removal rows. The soil at the site is predominantly from the Appling series (Fine, kaolinitic, thermic Typic Kanhapludults). The Appling series consists of very deep, well drained, moderately permeable soils on ridges and side slopes of the Piedmont uplands. These soils are deep to saprolite and very deep to bedrock. They formed in residuum weathered from felsic igneous and metamorphic rocks of the Piedmont uplands. Slopes at this site range from 2 to 15 percent.

Experimental Design

The experimental design was a randomized complete block design with four plots and nine treatments. Thirty-six plots of 0.25-acre (200 by 50 feet) were established in July 2005. The buffer area between each plot is approximately 100 feet. Each treatment area was approximately 1.03 acres.

Biosolid Application

Biosolids were applied in November 2005 and March 2006 using a side discharge spreader. The biosolids were not tilled into the soil. Collection trays were installed in each plot to accurately determine the amount of biosolids applied. Three different types of biosolids were used for this study from different locations (table 1). The anaerobically digested material was obtained from the Alexandria, VA and Back River, MD facilities. The lime stabilized biosolids were obtained from the Blue Plains facility (Washington, DC). The pelletized biosolids were obtained from the Baltimore, MD facility. The conventional fertilizer was based on common recommendations to loblolly pine plantations using urea + diammonium phosphate. Biosolids were applied at different target N loading rates, base on the amount of plant available N (PAN) estimated using established recommendations for VA (Evanylo 1999b). Treatment descriptions and biosolid characterization are listed in Table 1.

N Availability

In situ ion exchange membrane-N (IEM-N) was measured in all plots according to Cooperband and Logan (1994) and Huang and others (1996) procedures. Cation and anion exchange membrane sheets (Ionics Inc., Watertown, MA), were first cut into 13-square inch sheets. Cation and anion membrane squares were kept separate, washed with de-ionized water, and soaked inside plastic carboys containing 1 M NaCl solution every time they were used. Two sets of membranes were installed at random in the soil of each plot. After a 30-day incubation period individual membranes were then removed and stored at 4 °C until extraction with 1 M KCl. All extracts were analyzed colorometrically for nitrate (US EPA Method 353.2) and ammonium (US EPA Method 350.1) using a TRAACS 2000 Auto Analyzer (SEAL Analytical, Mequon, WI).

Foliage Weight Sampling

Foliage was sampled in each plot on February 1-7, 2007 following the procedure established by Colbert and Allen (1996). In each plot, five dominant or co-dominant trees were selected and marked. Then 20 fascicles from the 5 trees in each plot were composited to create a plot foliage sample of 100 fascicles. The foliage samples were dried in a forced air drying oven at 70 °C for 7 days. The oven-dried needle samples were then weighed and ground in a Wiley® mini-mill to pass through a 1 mm screen.

RESULTS AND DISCUSSION

Nitrogen availability was measured using IEM-N which is the sum of HN_4^+ and NO_3^- extracted from the membranes located at the top mineral soil and the forest floor. The total amount of N extracted was divided by the amount of days that they were buried in the field. Fall fertilization with lime stabilized and anaerobically digested biosolids increased total IEM-N from November 2005 to September 2006 in relation to the control treatment. The largest concentration of 36 mg-N/m^2/day was released by the anaerobically digested material in February. Total IEM-N concentrations for lime stabilized biosolids were elevated in May and July (fig. 1).

Spring biosolid application at different rates of anaerobically digested, lime stabilized, pelletized biosolid, and conventional fertilizer also significantly increased total IEM-N relative to the control treatment. Figure 2 shows the treatment increases in total IEM-N compared to the control treatments. There are no differences in total IEM-N among the 200 pounds per acre treatments, but N availability tended to last longer in biosolid applications than the conventional fertilization.

The main form of N in biosolids is organically bound N. This means that mineralization will play a key role in N availability (Hallett and others 1999). Given the large addition of organic N in both types of biosolids, we could expect that the N availability in the biosolids treated plots would remain higher than control plots for a longer period of time due to mineralization of organically bound N. Throughout the duration of this study biosolids applications increased soil IEM-N compared to control plots especially in the high rates biosolid treatments (fig. 2).

Trees respond to N availability by allocating more N to the foliage N. Increases in foliar N leads to increase foliar biomass, which then increase tree stem growth (Binkley and Reid 1984). Needles dry weight increased with biosolids applications, at both application times (fig. 3). The increases were not significant and not consistent with the biosolids loading rates. We may expect future significant responses since biosolids and fertilizer applications have shown to increase the tree foliage mass (Magesan and Wang 2002). Pelletized biosolids tended to have no effect on foliage weight; this could be explained due to the slower N release from the pellets.

Table 1—Treatment application rates and selected characteristics of the different biosolids

Treatments	Dry Weight (tons per acre)	Carbon (tons per acre) (pounds per acre)	Total N (tons per acre)	Effective PAN (pounds per acre)	pH
Fall Application					
Lime Stabilized 800	42.3	14.8	1.5	880	12.4
Anaer. Digested 800	31.5	9.8	1.57	935	8.2
Spring Application					
Lime Stabilized 200	10.3	3.6	3.8	220	12.2
Pellets 200	1.08	-	-	230	-
Urea + DAP 200	-	-	-	209	-
Anaer. Digested 200	7.7	2.4	0.4	223	8.5
Anaer. Digested 800	33.5	10.4	1.7	943	8.5
Anaer. Digested 1600	62.6	19.4	3.1	1820	8.5

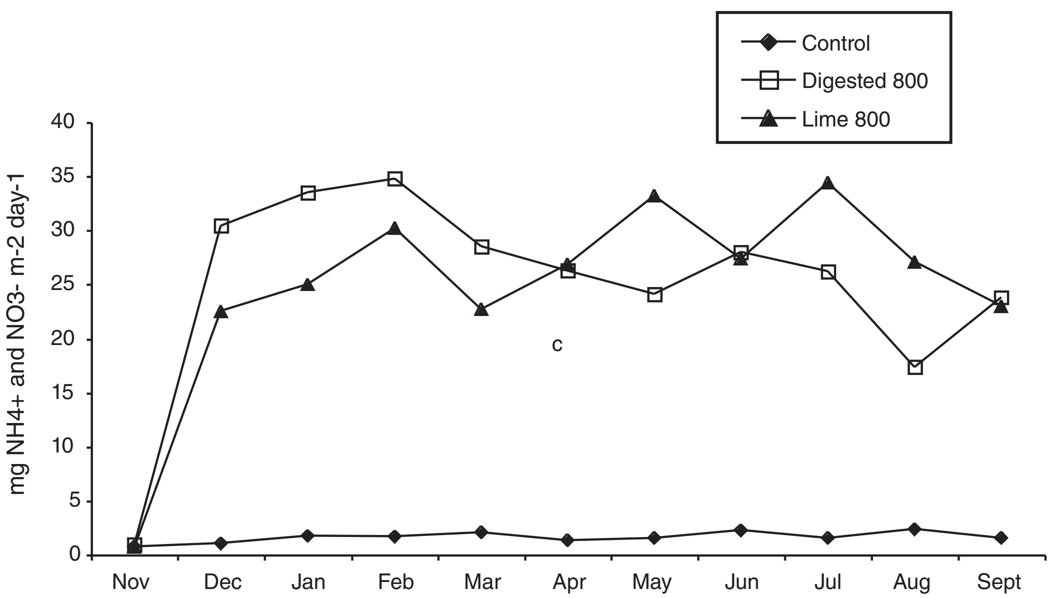

Figure 1—Total ion exchange membrane-NH4+ and NO3- from the forest floor and the upper 6 inches of mineral soil in a loblolly pine plantation in the Virginia Piedmont. Treatments are anaerobically digested and lime stabilized biosolids applied during November 2005 at a rate of 800 pounds per acre of plant available nitrogen (PAN), and reported in units of mg-N/m[2] of ion exchange membrane surface.

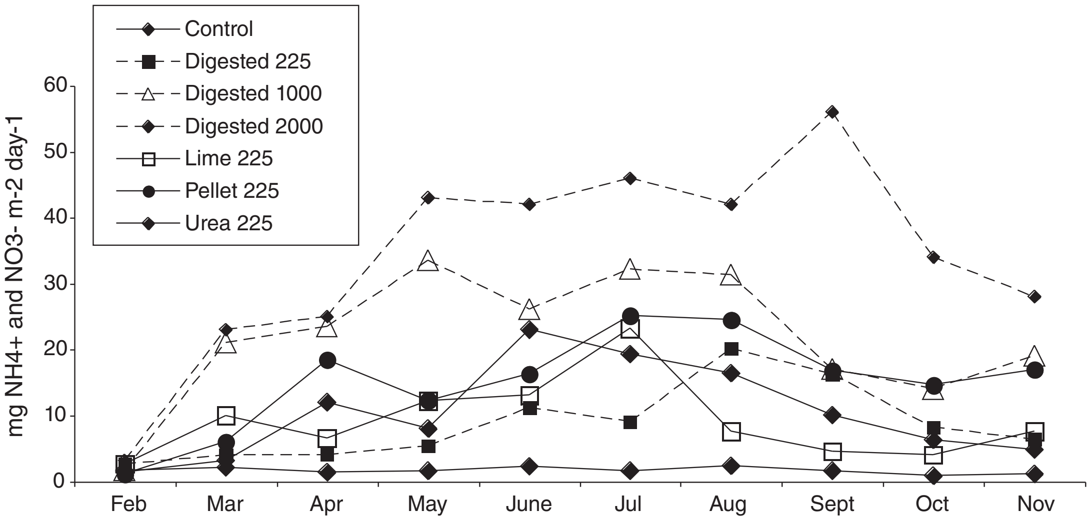

Figure 2—Total ion exchange membrane-NH4+ and NO3- from the forest floor and the upper 6 inches of mineral soil in a loblolly pine plantation in the Virginia Piedmont. Treatments are three rates of Anaerobically Digested biosolid (200, 800, and 1600 PAN), Lime Stabilized (200 PAN), pelletized biosolids (200 PAN), and conventional 200 pounds per acre of urea and DAP applied during March 2006, and reported in units of mg-N/m^2 of ion exchange membrane surface.

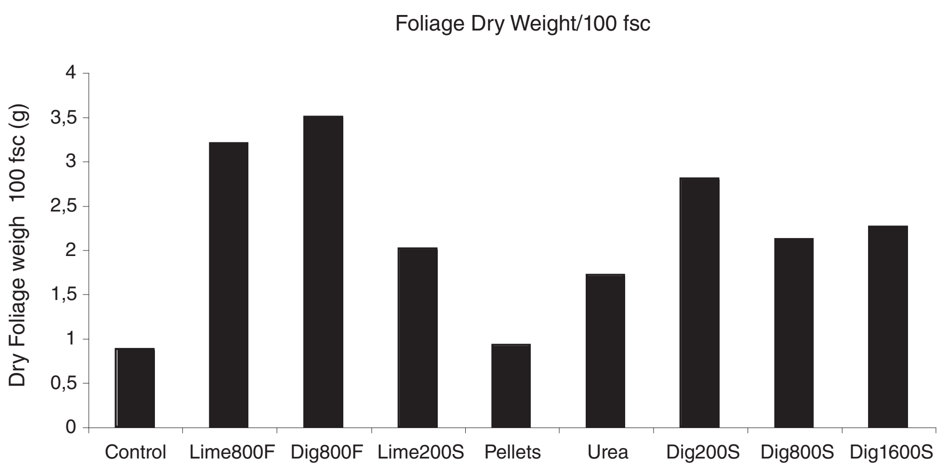

Figure 3—Total foliage dry mass of 100 needles sampled from a loblolly pine plantation in the Virginia Piedmont following treatment applications during November 2005 and March 2006. The first treatment applications were at one rate of anaerobically digested and lime stabilized biosolids (800 pounds per acre of PAN). The second treatment applications were at three different rates of anaerobically digested biosolid (200, 800, and 1600 pounds per acre PAN) and one application rate (200 pounds per acre PAN) of lime stabilized, pelletized biosolids, and a conventional urea + DAP treatment. Results are reported in mg/100 fascicles.

CONCLUSION

Preliminary results from this study indicate that biosolids additions increased soil nitrogen availability. Soil nitrogen availability following biosolids applications were greater than in the control plots. This occurred following both fall and spring treatment applications. Soil nutrient availability following biosolids was similar to that following application of inorganic fertilizer. Foliage mass increased in response to biosolids and fertilizer applications indicating there will likely be a positive effect on tree growth. Because the application of biosolids increased N availability in the soil, it also has the potential to increase N leaching. Several studies indicate that high application rates of biosolids increase the potential for nutrient leaching (Wells and others 1986, Ferrier and others 1996, and Jordan and others 1997). Additional work is underway to determine the leaching of N from these treatments.

The findings reported here and in other studies show that the characteristics of the biosolids being applied to land are as important as the site characteristics. Organic N forms, moisture content, and other soil chemical and physical properties could affect nutrient cycling and should be considered when applying biosolids.

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PROJECTED GROWTH AND YIELD AND CHANGES IN SOIL SITE PRODUCTIVITY FOR LOBLOLLY PINE STANDS 10 YEARS AFTER VARYING DEGREES OF HARVESTING DISTURBANCE

Mark H. Eisenbies, James A. Burger, W. Michael Aust, and Stephen C. Patterson[1]

Abstract—Southern industrial pine plantations are intensively managed. Shortened rotations and wet season trafficking can result in significant soil disturbances. This study investigated the effects of wet and dry weather harvesting, the ameliorative effect of bedding on soil site productivity on a rotation-length study, and compared the cost benefit of several site preparation treatments. Loblolly pine plantations were subjected to combinations of wet- and dry-weather harvesting and mechanical site preparation. Sites that were bedded had significantly more wood production at age 10 than non-bedded sites: approximately 60 and 45 tons/acre green-weight respectively. There were no significant differences between wet- and dry-weather harvested sites that were not bedded. Dry-weather harvested sites had the least production among the bedded sites, but there were few significant differences. Projected growth using the model FASTLOB2 suggests that flat-planted sites may be more profitable, but only if survival can be assured. This study also indicates that an experimental mole plow treatment can be productive and profitable, but requires further investigation on a wider variety of sites.

INTRODUCTION

Southern pine plantations are among the most intensively managed forests in the country (Allen and Campbell 1988). Forests in this region produce up to 400 cubic feet/acre annually (Borders and Bailey 2001), and due to limitations with mill inventories, they are harvested year-round. As a result, harvests during winter months, when evapotranspiration is minimal and soils are wet, results in soil impacts. Studies of trafficking disturbance have shown negative effects on soil properties and reductions in tree growth and survival (Aust and others 1995, Hatchell and others 1970, Lockaby and Vidrine 1984, Moehring and Rawls 1970, Scheerer 1994, Shoulders and Terry 1978, Youngberg 1959). Harvesting traffic during wet weather may cause rutting and compaction, erosion, nutrient loss, and organic matter disturbance (Greacen and Sands 1980, Kozlowski 1999, Miller and others 2004, Miwa and others 2004, Powers and others 1990, Sheriff and Nambiar 1995). In spite of literature that shows how forest practices can negatively affect soil chemical and physical properties related to tree growth, the direct link between forest operations and reduced productivity has been difficult to establish (Burger 1996, Morris and Miller 1994, Worrell and Hampson 1997).

Potential site impacts due to trafficking and biomass removal may be mediated both naturally and artificially (Cairns 1989, Vorhees 1983). The presence of shrink-swell clays can allow compacted soils to achieve lower bulk densities after multiple cycles of wetting and drying (McGowan and others 1983, Sarmah and others 1996). Soil biological activity, such as soil organisms or root systems, can benefit soil properties by contributing to the formation and stabilization of soil aggregates, alter soil structure, incorporate organic matter, and decrease bulk density (Jastrow and Miller 1991, Larson and Allmaras 1971, Oades 1993, Perfect and others 1990).

Intensive management practices may enhance site conditions, increase growth and yield, and improve economic return. Site preparation may also be used to ameliorate harvesting impacts. Bedding is a common site preparation practice on intensively managed plantations of the coastal plain recognized for its benefits for drainage, competition control, and nutrient allocation (Aust and others 1995, Coile 1952, Gent and others 1983, McKee and others 1985, Morris and Lowery 1988, Schultz and Wilhite 1974). Other types of mechanical site preparation include chopping, harrowing, disking, shearing, ripping, etc. (Smith 1986). Additional goals might include improving site drainage, as with drainage (Smith 1986) or mole plowing (Spoor and Fry 1983, Spoor and others 1982, Weil and others 1991). The main limitations of mechanical site preparation methods include the expense and potential impacts of repeated trafficking (Walstadm and Kuch 1987).

The long-term goal of this study is to evaluate (1) whether logging disturbances affect soil quality and loblolly pine (*Pinus taeda* L.) productivity on wet pine flats, and (2) can forestry practices mitigate disturbance effects if they exist? A specific objective of this paper is to evaluate the cost-benefit of an experimental mole plow treatment relative to more common site preparations.

METHODS

The study site is located on wet pine flats (Messina and Conner 1998) on the Atlantic Coastal Plain in Colleton County, SC. Three, 50-acre, bedded, loblolly pine plantations were selected as blocks in 1992 based on similar age (20-25 years), soil, and hydrologic conditions. The topography is flat to gently rolling marine terraces dissected by drainages. Soil parent materials consist of marine and fluvial sediments and feature the phosphatic Cooper Marl (Stuck 1982). Soils are poorly to somewhat poorly drained, and have an aquic moisture regime. Regionally, these sites are considered highly productive and are often intensively managed for the production of loblolly pine (*Pinus taeda L.*).

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Soils primarily consist of the Argent (fine, mixed, thermic, Typic Ochraqualfs) (57 percent), Coosaw (Loamy, siliceous, thermic Arenic Hapludults) (15 percent), Santee (Fine, mixed, thermic, Typic Argiaquolls) (13 percent), and Yemassee (Fine-loamy, siliceous, thermic Aeric Ochraquults) (14 percent) series. However, the sites are similar enough that they managed as a single unit. Surface drainage is largely controlled by microtopography and subsurface drainage by thick argillic horizons of low permeability that cause perched water tables (Xu and others 2002).

Five approximately 8-acre treatment areas were laid out as individual harvest units within each block including separate decks and skid trails (fig. 1). A sixth area in each block consisted of a no-harvest control, and was not used in this portion of the experiment. Prior to harvest each treatment area was overlain with a 66 by 66 feet grid. Within each of the 1170 1/10th-acre cells, a circular 1/50th-acre measurement subplot was permanently established.

In the fall of 1993, two randomly selected plots on each block were dry-weather harvested. In the spring of 1994, the remaining three plots on each block were harvested in wet conditions with the goal of maximizing soil disturbance. Harvesting was performed by conventional commercial logging operations using mechanized fellers and wide tired buncher/grapple skidders. The logger was instructed to treat the individual sites as they normally would for the site conditions that were encountered. Specifically, no effort was made to alter logger behavior. Disturbances were applied in this manner to ensure that the degree and distribution of both soil physical and harvesting residue disturbances would be operationally realistic.

Three levels of mechanical site preparation were applied in 1995: no mechanical site preparation (flat planting), conventional bedding, and an experimental mole plow

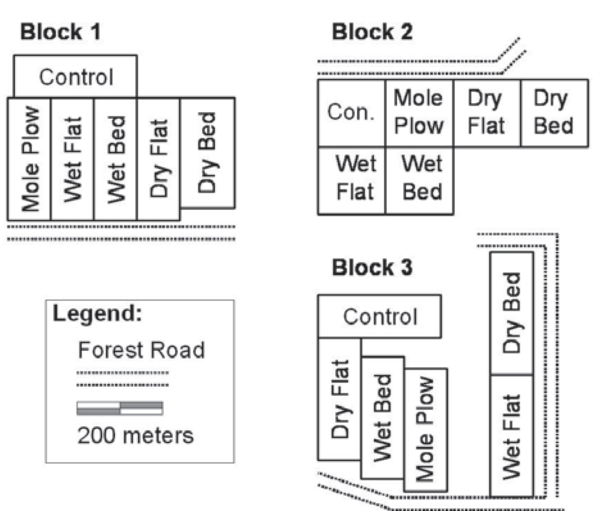

Figure 1—Block layout of individual harvesting units and corresponding treatments.

treatment. The purpose of the mole plow treatment was to facilitate water table equilibration via subsurface drainage in the argillic horizon for areas where rutting and churning may have disrupted normal drainage. Bedded sites were sheared and drum chopped prior to bed installation. Mole plowing was performed in October 1995 using a mole-shank and modified bedding plow, and then bedded in November 1995. Thus there were five treatments at the operational level: dry-harvested and flat-planted (DF), wet-harvested and flat-planted (WF), dry-harvested and bedded (DB), wet-harvested and bedded (WB), and wet-harvested, mole plowed and bedded (WMB).

All sites received chemical weed control in the form of Imazapyr (16 ounces/acre) and Glyphosate (76 ounces/acre) in July 1995. The sites were hand planted in February 1996 with best first generation, open-pollinated family, loblolly pine seedlings. As a precaution, non-bedded stands were double planted to emphasize treatment effects on productivity over that of stocking and survival effects. Extra seedlings were culled from double plantings that remained after the first year of growth.

Height and diameter breast height (d.b.h.) of all trees within the 1/10-acre subplots were measured prior to harvesting. Inventories of height and d.b.h. in the current rotation were conducted at ages two, five, and ten for the same 1/10-acre subplots across the entire study area. Site indexes (base age 25) were calculated at age 10 based on the height of a dominant or codominant tree nearest each 1/10-acre subplot center using equations developed for a range of loblolly pine site types (Amateis and Burkhart 1985). Green weight biomass was calculated as a function of height and d.b.h. (Bullock and Burkhart 2003, Phillips and McNab 1982).

An economic analysis was conducted by projecting growth and yield to the end of the rotation using the FASTLOB2 stand development model (Amateis and others 2005). Rotation lengths were optimized for individual treatment plots based on maximum net present value (NPV) at interest rates of 8 and 12 percent. The expressed site index and stocking at age 10 were used as surrogates for treatment effects in FASTLOB2. Biomass was assumed to be sold as pulpwood (4 inch d.b.h., $6 per ton), chip and saw (9 inch d.b.h., $21 per ton), or sawtimber (12 inch d.b.h., $38 per ton) using Southwide average prices obtained from Timber Mart South (University of GA) in February 2007. Treatment costs were estimated using regional trends (Dubois and others 2003). The assumed costs for flat-planted sites included hand planting ($48 per acre), fertilization ($65 per acre), chop and sheer ($100 per acre), and herbicides ($52 per acre). The assumed costs for bedded sites included the additional costs of bedding ($135 per acre). The cost of the experimental mole plow treatment was estimated to be approximately $100 per acre. Cost and benefits associated with taxes, hunting leases, and other sources of revenue were not considered.

Maximum NPV, stand age, and biomass were evaluated at the operational scale using the general linear model at the alpha = 0.05 level (Hicks and Turner 1999). Means separations were conducted using Fishers' protected least significant difference. The covariates prior stand production and site index were considered, but not found to be significant.

RESULTS AND DISCUSSION

Disturbance Response

In a review of harvesting disturbance from the 1960s to the 1980s, Reisinger and others (1988) reported that greater than 63 percent of logging areas remain undisturbed after harvesting operations. At the time of treatment installation, deep rutting was considered excessive in SC when 20 to 25 percent of the site is affected (Tim Adams, SC Forestry Commission, Personal Communication, 1994). The wet-weather harvesting treatments were designed to maximize soil disturbance. While soil compaction occurred on less than 10 percent of dry-weather harvested sites, wet-weather harvested sites were over 60 percent disturbed including compaction, rutting, and churning (Eisenbies and others 2006). Between 26 and 44 tons per acre of harvesting residues were distributed across the sites with greater quantities found on wet-harvested sites (Eisenbies and others 2002). Loggers topped trees where they were felled on wet-harvested sites in order to increase tire floatation and reduce drag on wet harvested sites. On dry harvested sites whole trees were skidded to delimbing gates near the landings.

Production was greatest on bedded sites, but no significant differences were found between wet- and dry-harvested sites (Eisenbies and others 2007). The benefits of bedding loblolly pine stands are already well established (Aust and others 1995, Gent and others 1983, McKee and others 1985, Miller and others 2004, Miwa and others 2004, Morris and Lowery 1988, Schultz and Wilhite 1974, Terry and Hughes 1975). However, no changes in soil-site productivity were detected among non-bedded (DF and WF) and bedded (DB, WB, and WMB) sites except with regards to height growth on flat-planted sites. Eisenbies and others (2007) noted that survival was very high on flat-planted sites due to relatively dry conditions for the first few years of growth. They also observed that localized areas where moderate amounts of disturbance occurred appeared to perform better than less disturbed areas, and that soil bulk density and porosity were also improve over time due to bedding and natural processes.

Simulation Results

These sites are projected to produce between 134 and 260 tons/acre when their net present values are maximized at 8 and 12 percent (table 1). The wet-harvested, mole plowed and bedded sites are projected to have the highest production of the five treatments. There is some evidence that the MP sites may have had slightly higher initial site quality (Eisenbies and others 2006). Optimized rotations lengths based on cost estimates and current estimates for timber prices are between 16 and 33 years. Higher costs and higher interest rates logically result in the maximum NPV being attained earlier in the rotation. Simulated mortality on flat-planted sites only resulted in 2 year delay in rotation age, but there was no change in actual yield.

Although the WMB treatment had significantly higher simulated production, it did not generate significantly higher income than the other bedded sites in most cases (table 2). The flat-planted sites were the most profitable within blocks, but rarely significantly so and not when a planting failure was simulated. One limitation is that the simulations do assume that current separation between treatments will be maintained for another 10 years; however, apparent changes in soil-site productivity have been converging with time (Eisenbies and others 2007). Additionally, FASTLOB2 seems to predict slightly high yields from age 10 data. These sites were unusually productive for coastal plain plantations due to the parent material and have high site indexes. Thus, either the model's capacity to accurately simulate these sites may be impaired, or the site index curves utilized are too general and overestimate some stands.

The comparatively high costs of operating heavy machinery may favor flat-planting economically, especially if interest rates rise; however, site-preparation may remain the best choice in order to ensure proper stocking. It is also difficult to recommend the WMB treatment despite its higher predicted

Table 1—Predicted age and yield where net present value is maximized based on FASTLOB2 simulations from age 10 for five harvesting/site preparation treatments

Treatment	-------------- 8 percent --------------		-------------- 12 percent --------------	
	Harvest Age	Yield	Harvest Age	Yield
	years	*tons/acre*	*years*	*tons/acre*
DF	30.0 bc	200 c	18.3 ab	134 c
WF	33.3 a	230 b	19.0 a	147 bc
DB	32.3 ab	240 b	18.3 ab	156 b
WB	30.7 bc	240 b	17.3 bc	156 b
WMB	29.0 c	260 a	16.0 b	179 a

Table 2—Comparison of maximum net present value (in dollars) predicted using four FASTLOB2 simulations for five combinations of harvesting treatments

Treatment	Maximum Net Present Value			
	Block 1	Block 2	Block 3	Total
	---------------------- 8 percent IR without Mortality ----------------------			
DF	145	244	18	135 a
WF	107	178	46	110 a
DB	74	104	-97	27 b
WB	-18	150	39	57 ab
WMB	114	162	-101	58 ab
	------------------------ 8 percent IR with Mortality ------------------------			
DF	31	115	-78	16 a
WF	13	74	-39	22 a
DB	74	104	-97	27 a
WB	-18	150	39	57 a
WMB	114	162	-101	58 a
	--------------------- 12 percent IR without Mortality ---------------------			
DF	-89	-36	-163	-96 a
WF	-122	-85	-157	-121 a
DB	-195	-181	-291	-223 b
WB	-247	-146	-220	-204 b
WMB	-201	-163	-345	-236 b
	----------------------- 12 percent IR with Mortality -----------------------			
DF	-185	-143	-244	-191 a
WF	-189	-160	-217	-189 a
DB	-195	-181	-291	-223 a
WB	-247	-146	-220	-204 a
WMB	-201	-163	-345	-236 a

yield without more replication on a wider variety of sites. Although few clear economic decisions can be drawn from this study, the opportunity to compare the experimental site preparation against more common practices is valuable.

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DOUBLE-PLANTING CAN AFFECT GAINS FROM WEED CONTROL TREATMENTS

David B. South[1]

Abstract—Double-planting is the practice of planting two seedlings at every planting spot. When both seedlings survive, then either the less vigorous seedling is removed or each seedling is given an equal chance of being removed. Some researchers double-plant so that tree growth among experimental plots is not affected by initial differences in stocking. However, double-planting might have an effect on conclusions when the response variable is affected by initial survival. A growth and yield program was used to estimate the effects of double-planting on yields obtained from eliminating hardwood competition. As expected, increasing stocking (by double-planting) increased standing volume at age 25 year. If the herbicide treatment increased survival, the predicted increase was greater for double-planting than for single-planting. However, when the use of herbicides reduced seedling survival, the predicted increase in volume gains was greater for single-planted stands.

INTRODUCTION

"Double-planting" involves the practice of planting two seedlings at every planting spot (typically from 0.1 to 0.5 m apart). This is done in hopes that most planting spots will have at least one live seedling a year after planting. When both seedlings are alive then one is removed. In some studies, the less vigorous seedling is removed while in others each seedling is given an equal chance of being removed. It is not known when this practice began but Powers (1979) double-planted seedlings in December of 1978. Its popularity has increased among researchers in the Southern United States (table 1). Some researchers are concerned that when planting one tree per planting spot (i.e. single-planting), first-year survival might be less than 90 percent and that stocking might vary by treatment. Therefore in South Africa, researchers and some companies single-plant and then replant the "blank spots" a month later (a.k.a. blanking). Blanking is known as "beating-up" in the United Kingdom and "interplanting" in the United States. Occasionally, interplantaing is practiced when initial survival is decreased by the application of chemicals (Edwards 1994, Haywood and Tairks 1990). However, since analytical problems can occur with interplanting, some researchers prefer to double-plant seedlings. In one study in California, double-planting plus interplanting were used to ensure one tree per planting spot (York and others 2004).

ECONOMICS

The reason double-planting is rarely practiced operationally is due to higher establishment costs. For example, if a bare-root longleaf pine (*Pinus palustris* Mill.) seedling costs 8 cents each and it costs 7 cents to plant a tree by hand, double-planting would cost about 33 cents per planting spot (removing doubles might cost $50/ha). Planting container seedlings might cost only 24 cents per seedling (17 cents for seedlings plus planting costs). However, double-planting is used in some parts of Africa. In semi-arid areas of Kenya, some farmers (about 1 out of 10) will plant two seedlings in each pit (Roothaert and others 2003).

RESEARCH TRIALS

Double-planting is practiced mostly by researchers in the United States although it has been used in Sweden and Brazil (Johansson 2004, Pereira and Vale 1984). In Italy, double planting has been used in cherry and oak plantations (Buresti and others 2001, 2003). Seven years after planting, the less vigorous and/or poorly formed seedling is removed. Although many establishment trials are established in Canada, China, the United Kingdom, South Africa, New Zealand and in Australia, double-planting is rarely practiced in these countries. It is possible that some trials were double-planted but the practice was not mentioned in the methods section (e.g. Nowak and Berisford 2002).

Some researchers have experienced planting failures and therefore they double-plant to reduce the risk of failure. Low survival after planting bare-root, loblolly pine (*Pinus taeda* L.) or slash pine (*Pinus elliottii* Engelm.) might be related to: (1) planting stock with root-collars less than 5 mm; (2) a reluctance to plant seedlings deep—with the root-collar 15 cm below ground; (3) using inexperienced hand-planting crews; (4) allowing tree planters to prune or strip roots in order to avoid bent roots in the planting hole; and (5) planting late (i.e. after March 1). Some researchers will prune roots to facilitate hand planting (e.g. Wilder-Ayers and Toliver 1987) even though pruning roots will increase the shoot/root ratio and will reduce the chance of seedling survival (Harrington and Howell 1998, South 2005). Likewise, transplanting seedlings just prior to a hard freeze can reduce longleaf pine survival (South and Loewenstein 1994). To provide a buffer against improper planting techniques or weather events, some researchers double-plant (which can increase stocking levels up to 25 percent). Instead of double-planting, geneticists often choose to single-plant, container-grown loblolly pines.

DOES IT AFFECT RESULTS?

Double-planting will have no effect on results and conclusions of some experimental trials. For example, if the objective is to examine the effect of ozone concentration of seedling physiology, then double-planting will not alter the conclusions. However, double-planting might affect the results if the response variable of interest is: (1) stocking or (2) per hectare volume.

The survival percentage (i.e. number alive/number planted) is not affected by double-planting but stocking level (live trees/ha after thinning at the end of the first growing season) will be

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Table 1—A partial list of double-planted experiments in the United States

Species	Study involves	Reference
Pinus taeda	Ozone	Barbo and others 2002
	Fertilization	Borders and others 2004
	Tillage	Carlson and others 2006
	Logging	Eisenbies and others 2006
	Topography	Haywood 1983
	Tillage and Fertilization	Haywood 1995
	Logging method	Laihoa and others 2003
	Site preparation	Martin and Shiver 2002
	Mycorrhizae	McLellan and others 1995
	Weed competition	Miller and others 1991
	Fertigation	Nowak and Berisford 2000
	Spacing	Rahman and others 2006
	Second-rotation	Rose and Shiver 2000
	Second-rotation	Rubilar 2003
	Ozone	Sasek and others 1991
	Ozone	Stow and others 1992
Populus deltoides	Genetics	Foster 1986
	Genetics	Foster and others 1998
	Genetics	Knowe and others 1994
Western conifers	Opening size	York and others 2004

affected. Even so, some claim that double-planting increases seedling survival (Rahman 2006). However, in this case it would have been appropriate to state that stocking level averaged 94 percent (instead of saying that seedling survival was 94 percent). A stocking level of 94 percent suggests that seedling survival was approximately 76 percent.

When survival is 50 percent, double-planting will increase stocking level to 75 percent (fig. 1). In some cases, single-planting morphologically improved seedlings (with 8 or 9 mm root-collars) will result in fewer empty spots than double-planting typical seedlings with 4 mm root-collars (fig. 1).

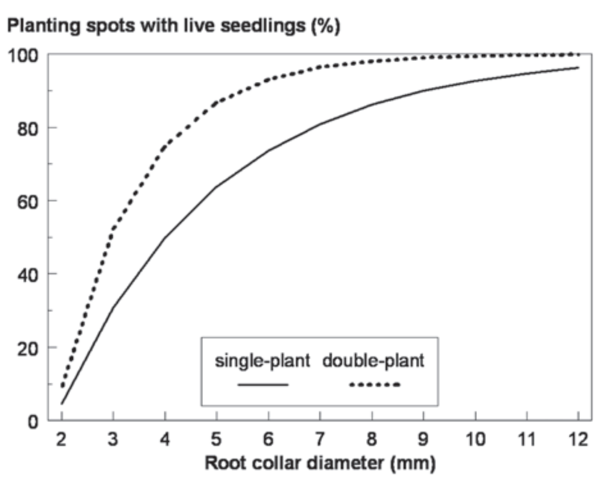

Figure 1—The potential effect of double-planting on stocking of slash pine in Georgia. The single-planted stand is represented by the equation $Y = 100\text{-}10^{(2.26\text{-}0.145X)}$ where Y is 3rd-yr survival and X is the root-collar diameter at time of planting. The increase in stocking due to double-planting was greatest when planting seedlings in the 4 to 6 mm range. Survival on this site was greater than 90 percent when seedlings with large roots (e.g. RCD > 9 mm) were machine planted (South and Mitchell 1999).

However, many researchers prefer to double-plant 4-mm seedlings than to single-plant 8- or 9-mm seedlings.

For loblolly pine, volume gains from controlling herbaceous weeds can increase as pine stocking increases. Quicke and others (1999) report volume gains (at age 15 years) from weed control might be 2 m^3/ha at a stocking of 800/ha while gains were 9.2 m^3/ha when seedlings were planted at 2200/ha. Therefore, as initial stocking levels increase, pine production will be increased (at least at ages 15 to 20 years). The question then becomes, when the difference in initial stocking level is minimized, does the volume gain (from weed control) decrease? Outputs from a growth and yield model were used to address this question.

METHODS

The North Carolina State University Growth and Yield Simulator was used to predict yields from controlling hardwoods in loblolly pine plantations in the Piedmont. Inputs included 1,200 spots/ha and the site quality would produce an average height of dominants and co-dominants of 22.9 m at age 25 years. The theoretical herbicide treatment eliminated competition from hardwoods while nontreated stands contained 20 percent of the basal area in hardwoods (at age 10 years). Four simulations were conducted. On Site #1, the herbicide treatments did not affect seedling survival while they reduced survival on Site #2. Herbicide use on Site #3 increased survival by 10 percentage points (i.e. from 80 percent to 90 percent) while on Site #4 survival increased by 25 points (i.e. from 50 percent to 75 percent). The following equation was used to estimate stocking level: Stocking = survival + [(1- survival)*(survival)]. For example, a stocking level of 84 percent is obtained by double-planting when survival is 60 percent: 0.84 = [(1-0.6)*(0.6)] + 0.6.

RESULTS AND DISCUSSION

As expected, eliminating hardwood competition increased volume production for all four sites (table 2). The increase was greatest for the low-survival site and was lowest for the site where herbicides reduced survival.

Table 2—Predicted effects of planting method and hardwood control on volume production at age 25 years (modeled output from NCSU Plantation Simulator)

Site	Herbicides	Hardwood competition	Initial survival	Planting method	Stocking (1^{st} yr)	Volume (m^3/ha)	Gain due to weed control (m^3/ha)
#1	Yes	None	80%	Double	96%	334	62
	No	20%	80%	Double	96%	272	--
	Yes	None	80%	Single	80%	323	59
	No	20%	80%	Single	80%	264	--
#2	Yes	None	70%	Double	91%	332	60
	No	20%	80%	Double	96%	272	--
	Yes	None	70%	Single	70%	313	49
	No	20%	80%	Single	80%	264	--
#3	Yes	None	90%	Double	99%	336	64
	No	20%	80%	Double	96%	272	--
	Yes	None	90%	Single	90%	331	67
	No	20%	80%	Single	80%	264	--
#4	Yes	None	75%	Double	94%	333	73
	No	20%	50%	Double	75%	260	--
	Yes	None	75%	Single	75%	318	84
	No	20%	50%	Single	50%	234	--

Site index = 23 m in 25 years; 1200 planting spots per ha; 20% = amount of basal area in hardwood trees.

Regardless of site, double-planting increased stocking and volume production. At two sites (#1 and #2), double-planting increased the gain from weed control. For the sites where herbicide treatment increased survival (sites #3 and #4), double-planting reduced volume gains by 3 to 11 m^3/ha. On sites where double-planting does not increase stocking, there will be little or no effects of double-planting on treatment response.

On Site #2, the application of herbicides reduced survival by 10 percentage points. This is similar to what was observed at Liberty, MS (Miller and others 1995) where hardwoods sprouts were treated with herbicides and survival was reduced by about 12 percent (fig. 2). The use of herbicides has reduced survival of pine seedlings in several research trials (Barnard and others 1995, Quicke and others 1999, South and others 1995). In one study, seedlings treated with hexazinone had 64 percent survival while plots not treated had 93 percent survival (Edwards 1994).

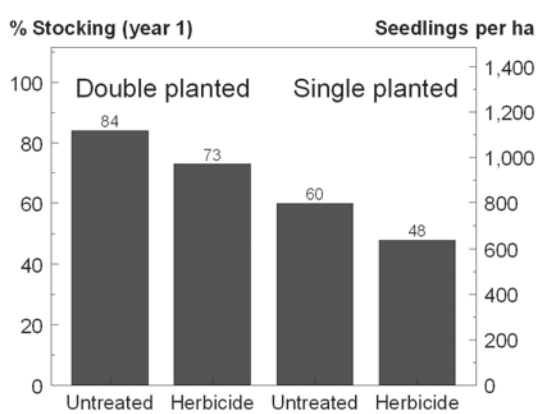

Figure 2—An example of the effects of double- planting and use of herbicides on first-year stocking of loblolly pine at Liberty, MS (double-planting results from Miller and others 1995—single-planting results are estimates).

CONCLUSIONS

Researchers double-plant to reduce the risk of low seedling survival and to minimize the variation in survival among experimental units. When seedling survival or volume/ha are not reported, double-planting will not affect the conclusions. In some cases where herbicides increase seedling survival, volume gains obtained from the weed control may be reduced by double-planting. This effect is expected by those researchers who want to eliminate stocking effects from growth related treatment responses. However, double-planting might increase volume gains on sites where stocking is either reduced or unaffected by herbicide use. These results are likely dependent on the growth and yield model employed.

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RELATIONSHIP BETWEEN HERBACEOUS LAYER, STAND, AND SITE VARIABLES IN THE BANKHEAD NATIONAL FOREST, ALABAMA

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Abstract—We studied herbaceous layer richness, diversity and cover in stands on the southern Cumberland Plateau. The stands are mixed pine-hardwoods dominated by 25-40-year-old planted loblolly pine (*Pinus taeda* L.). Scheduled future treatments combining thinning and fire are designed to restore the hardwood component, particularly oak (*Quercus* spp.) and hickory (*Carya* spp.) species, and to increase herbaceous diversity. We related pretreatment herbaceous layer (vegetation < 1.4 m height) richness, diversity, and cover to basal area and site variables on 125 plots in 25 stands. Our models showed significant but weak relationships. Slope, broadleaf litter cover, and basal area accounted for 14 percent of the herbaceous layer richness. Models for species diversity and cover had lower coefficients of determination. The measured stand and site variables were not reliable predictors of pretreatment herbaceous layer variation.

INTRODUCTION

Floral diversity of temperate forests in eastern North America is highest in the herbaceous layer (classified as vegetation < 1-2 m in different sources) (Braun 1950, Gilliam and Roberts 2003). Composition of the herbaceous layer is also influenced by stand conditions, which are often modified by silvicultural treatments and natural disturbance events (Royo and Carson 2006). Concerns about biodiversity loss have caused forest managers to use silvicultural practices that promote biodiversity and alter species composition (Burton and others 1992).

Future silvicultural activities on the William B. Bankhead National Forest (BNF) are also designed with biodiversity in mind, mostly in response to recent outbreaks of southern pine beetle (*Dendroctonus frontalis* Zimm) and in an effort to restore stands on ridge tops currently dominated by planted loblolly pine (*Pinus taeda* L.) to oak (*Quercus* spp.)–hickory (*Carya* spp.), and mixed hardwood. The desired future community has been found to hold the highest diversity in the herbaceous layer (Monk and others 1969) and ought to be characterized before silvicultural treatments begin.

Past studies relating herbaceous layer data to environmental variables report that slope and especially aspect (Clanton 1953, McCarthy and others 1987), in addition to soil moisture (Wayman and North 2007), tend to have the strongest influence on richness, diversity, and cover in the herbaceous layer. Small and McCarthy (2002) suggest that topographical variation and ecosystem properties be well-studied along with disturbance responses. In the central hardwoods region and the southern Cumberland region, there remains a need for in depth herbaceous layer studies given the wide variety of results and lack of consistent findings on herbaceous layer dynamics (Gilliam and Roberts 2003).

Our study objectives were to 1) quantify herbaceous layer species richness, diversity, and cover; 2) determine their relationships to pretreatment basal area and site variables (slope, aspect, broadleaf litter, pine leaf litter, and moisture); and 3) establish baseline characterization of the plant communities of the ridge tops in the BNF. This work is a part of a multidisciplinary forest ecosystem response study to nine silvicultural treatments. Our null hypotheses were that site and stand variables would not be significant predictors of species richness, diversity, and cover in the herbaceous layer.

METHODS

Study Area

The study took place in the Bankhead National Forest (BNF) on the southern Cumberland Plateau (N 34°19' W087°21') in Lawrence, Winston, and Franklin counties in northwest AL. Study stands are all located on or near ridge tops of the plateau and are composed of mixed pine-hardwoods (approximately 75 and 25 percent of the basal area, respectively) dominated by planted loblolly pine. Approximate stand ages range from 25 to 40 years. Average total basal area in each stand is 38 m^2/ha ± 10 SD (range 18-67). Precipitation is approximately 145 cm per year (Sipsey Fork near Grayson, AL, USGS Station 02450250). Soil pH ranged from 4.5 to 5.8 (Dillon 2006). The soils were sandy Ultisols on limestone bedrock, well drained, and permeable Typic Hapludults (Smalley 1982). Elevation ranges from 219 to 300 m. Scheduled silvicultural treatments are nine combinations of three levels of low intensity dormant season prescription burns—frequent (3 to 5 years), infrequent (8 to 10 years), and control (no burn), and three levels of partial overstory removal, which is a free thinning to favor the hardwoods—heavy thin (residual basal area 11 m^2/ha), light thin (residual basal area 17 m^2/ha) and control (no thin). Treatments will be replicated four times. Post-treatment herbaceous layer sampling is planned and will be carried out three times during the growing season.

Herbaceous Layer Sampling

All vegetation < 1.4 m in height was sampled in 25 of the 36 stands selected for future treatment at the BNF. The other 11 stands had already been treated at the time of the sampling.

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Herbaceous layer vegetation plots were situated within five permanently marked, concentric circular nested 0.08-ha woody vegetation plots in each stand. Imposed upon each of the woody vegetation plots were 4 subplots, each 4-m^2, to measure herbaceous layer vegetation. The area sampled in each of the 125 plots totaled 16 m^2. Cover was determined by ocular estimates to the nearest 1 percent and totaled 100 percent since overlap was uncommon. All vascular plants were identified to species whenever possible. Specific nomenclature follows that of Radford and others (1968).

Stand and Site Variables

All trees with diameter at breast height (d.b.h., 1.37 m above ground) greater than 3.8 cm were used to calculate basal area in each of five 0.01-ha circular plots, nested within the 0.08-ha plots. At each subplot, area not covered by live vegetation or other ground variables (e.g. rock, bare soil, tree bole, etc.) was categorized as either pine litter or broadleaf litter. Broadleaf and pine litter cover were also used as predictor site variables in this study because of the different physical, chemical, and biotic influences they have on the soil and distribution of plant species (Facelli and Pickett 1991). However, they were not included as predictor variables in the model for plant cover because of collinearity between the two variables. Slope and aspect were collected from the center of each plot. Aspect was transformed to a northness (cos[Aspect]) and eastness (sin[Aspect]) component where a value of 1 for northness represented due north and -1 represented due south. Likewise, a value of 1 for eastness represented due east and -1 represented due west. The moisture index (MI) used in this study was generated in ArcGIS (ESRI, Redlands, CA, USA) with a digital elevation model (10-m resolution) using the ratio of slope to specific watershed area (Beven and Kirby 1979):

$$MI = \ln(WA/tg(\beta)) \qquad (1)$$

where WA is the watershed area of the pixel and $tg(\beta)$ is the local slope. A mean of this index was generated for each plot.

Data Analysis

Diversity was represented by the Shannon-Wiener index (H') calculated with the formula (Magurran 1988):

$$H' = -\sum p_i \ln p_i \qquad (2)$$

where p_i is the proportion of all individuals in sample that belongs to the *i*th species.

Species richness was the number of species in each sample unit (i.e., the plot). Multiple linear regression analysis with stepwise variable selection was used to relate herbaceous layer cover, richness (number of species - S'), and diversity (H') to basal area and site variables using SAS V. 9.1.3 (SAS 2005). Each plot was treated as a sample (n = 125). Because each of the plots is 33 to 498 m apart ($\bar{X}$ = 197 ± 105 SD), we treated them as independent from one another.

RESULTS AND DISCUSSION

Average pretreatment stand-scale (averaged for all 5 plots per stand) herbaceous layer cover was 32 percent, species richness was 57, and Shannon-Wiener Index (H') was 2.74. Across all 25 stands, we found 165 vascular species, 127 genera, and 62 families. This is similar to findings on dry mixed hardwood and pine-hardwood stands in the Southern Appalachians where species richness was less than 200 (Clinton and Vose 2000, Elliot and Knoepp 2005). Fifteen of the most frequently occurring vine, herbaceous, and graminoid species, five from each of three different life forms, included species that also represent much of the relatively sparse cover that exist on these sites (table 1). Slope varied from 0 to 19.9 degrees ($\bar{X}$ = 7.9) and aspect varied considerably across all 25 stands and within any given stand (table 2).

We found herbaceous layer species richness to have significant negative association with the predictor variables broadleaf litter cover and slope, but positive association with basal area (table 3). The overall model was highly significant (p-value < 0.01), but the model accounted for only 14 percent of the total variance in the data (table 3). The independent variables slope and eastness were significant predictors of species diversity (model P = 0.06), while slope and mean moisture index were significant predictors of vascular plant cover (model P = 0.02). However, the models R^2 were low, 5 and 6 percent, respectively (table 3). The parameter estimates indicated that a change in the mean moisture index value would result in much larger response in vascular plant cover than changes in the slope. The negative association between cover and moisture index also suggests that there is higher cover of vascular plants on drier sites. The low fit of the models indicate that that the relationship between the dependent and independent variables may be non-linear or that other variables that we did not measure have stronger influence on richness, diversity, and cover.

Pretreatment herbaceous layer richness and diversity were low in the studied stands at the BNF most likely because of the closed canopy, low light conditions, and limited moisture on the plateau ridge tops. Although there were a number of variables in the model that were significant, basal area and the measured site variables did not account for much of the variance in herbaceous layer richness, diversity, and cover at the plot level. Other variables not considered, such as burn history (Joyce and Baker 1986) and land use (Flinn and Velland 2005) are likely contributing to variation in the herbaceous layer and will have to be taken into account in future analysis.

Thinning, dormant season prescribed burning, and combinations of thinning and burning in a randomized complete block design will be applied to the stands. This study will establish the baseline data upon which to investigate long-term response to silvicultural practices in these plant communities. We expect that stronger relationships between herbaceous layer vegetation and environmental variables will emerge after the treatments and that richness, diversity, and cover will increase post-treatment as has recently been found in other studies from the region (Hutchinson and others 2005, Zenner and other 2006).

Table 1—Five most frequently occurring species of 3 life forms in 25 mixed pine-hardwood stands at the Bankhead National Forest, AL (listed alphabetically for each life form)

Life Form	Scientific Name	Common Name	Cover	Frequency
			----- *percent* -----	
	Berchemia scandens (Hill) K.Koch	Supplejack	1.8	38
	Gelsemium sempervirens (L.) Ait.	Yellow jessamine	1.2	31
Vines	*Smilax rotundifolia* L.	Roundleaf greenbrier	2.0	98
	Rhus radicans L.	Poison ivy	3.2	75
	Vitis rotundifolia Mich.	Muscadine	8.5	93
	Chimaphila maculata (L.) Pursh	Pipsissewa	0.2	54
	Lespedeza procumbens Mich.	Creeping bush clover	1.0	9
Herbaceous	*Mitchella repens* L.	Partridge berry	2.9	13
	Polystichum acrostichoides (Mich.) Schott	Christmas fern	2.5	14
	Solidago arguta Ait.	Atlantic goldenrod	0.6	26
	Carex picta Steud. *	Boott's sedge	3.5	38
	Danthonia spicata (L.) Beauvois	Poverty oat-grass	0.5	6
Graminoids	*Scleria oligantha* Mich.	Nut rush	0.7	15
	Stipa avenacea L.	Needlegrass	1.4	60
	Uniola sessiflora Poir.	Spanglegrass	2.1	12

* not found in Radford and others (1968); accepted by ITIS (Integrated Taxonomic Information System)

Table 2—Mean, standard error, minimum, and maximum for variables from 125 plots that were used in the analysis

Variable	Mean	Standard Deviation	Minimum	Maximum
Independent				
Slope (°)	7.8	4.1	0.5	19.9
Eastness	-0.12	0.67	-1.0	1.0
Northness	-0.09	0.73	-1.0	1.0
Basal area (m^2/ha on 0.01 ha plot)	38.0	10.0	18.2	67.9
Pine litter cover (%)	38.2	13.4	7.5	68.4
Broadleaf litter cover (%)	25.0	9.2	9.2	56.3
Moisture Index	0.003	0.001	<0.001	0.008
Dependent				
Species richness (S')	11.1	3.0	5.0	20.5
Species diversity (H')	1.56	0.27	0.93	2.20
Cover (%)	33.0	15.9	4.8	71.0

Table 3—Selected predictor variables, parameter estimates, and overall model P-value and R^2 for multiple linear regression using the stepwise variable selection. The predictor variables were chosen from among the stand and site variables

Dependent and predictor variable	Parameter Est.	Standard Error	P-value	Model P-value	Model R^2
Species Richness (S'):					
Intercept	13.15	1.32	<0.01		
Broadleaf litter cover	-0.05	0.02	0.01	<0.01	0.14
Slope	-0.16	0.06	0.01		
Basal area (0.01 ha plot)	0.04	0.03	0.15		
Species Diversity (H'):					
Intercept	1.65	0.06	<0.01		
Slope	-0.01	0.01	0.06	0.06	0.05
Eastness	0.07	0.04	0.08		
Vascular Plant Cover (%):					
Intercept	43.90	4.27	<0.01		
Slope	-0.70	0.35	0.05	0.02	0.06
Mean moisture index	-2051.48	1191.07	0.09		

Such relationships and increases should be captured as we study the initial impacts of the silvicultural treatments on herbaceous layer dynamics.

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Invasives

Moderator:

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THE FACILITATION AND IMPACTS OF *MICROSTEGIUM VIMINEUM* COLONIZATION IN AN EASTERN HARDWOOD FOREST

Christopher M. Oswalt and Sonja N. Oswalt[1]

Abstract—*Microstegium vimineum* is an annual, invasive Asian grass that occurs across the southeastern United States. Research on *M. vimineum* suggests there is a suite of environmental conditions that contribute to the species' spread. We have synthesized the results of two studies that tested 1) the effects of winter litter disturbance on the spread of *M. vimineum* under various canopy conditions, and 2) the impacts that establishment and growth of *M. vimineum* have on woody species density and diversity. Plots with winter litter disturbance experienced *M. vimineum* expansion rates 4.5 times those measured in undisturbed plots. Native woody species density and diversity both decreased with increasing *M. vimineum* percent cover. Land managers who have found *M. vimineum* on the forestland they manage may benefit by removing the species prior to any site manipulation to avoid the plant's spread and a subsequent decline in woody regeneration success.

INTRODUCTION

Microstegium vimineum is an annual, shade-tolerant grass introduced from Asia into the southern United States in the early 1900s (Barden 1987). The species is identified by its sprawling form, alternate leaf arrangement, and lanceolate, sparsely hairy leaves with offset mid-vein (Miller 2003). With its rapid invasion in many southern forests and floodplains, *M. vimineum* has garnered attention in the last few decades (Barden 1987, Horton and Neufield 1998, Oswalt and others 2004, Cole and Weltzin 2004, Buckley and Marshall 2005, Cole and Weltzin 2005, Oswalt and others 2007). Multiple, interacting mechanisms combined with *M. vimineum's* ability to compensate for light and/or moisture limitations have hampered researchers' efforts to narrowly define the driver(s) of *M. vimineum* distribution. *M. vimineum* can persist year after year as a small, inconspicuous plant in low-light conditions (Horton and Neufeld 1998) while producing copious seed that may persist in the soil for 3 to 5 years, and that vigorously respond to increased light (Barden 1987, Miller 2003, Oswalt and others 2004, Oswalt and others 2007).

Barden (1987) found that *M vimineum* was able to rapidly invade floodplain forests in North Carolina following canopy disturbance. Cole and Weltzin (2004) documented negative correlations between *M. vimineum* biomass and litter mass in all but one site (a clearcut) in a Tennessee study. The overall plasticity of the species and its wide ecological amplitude suggest that a variety of environmental factors facilitate spread and growth, including light availability associated with canopy density and light availability associated with litter on the forest floor.

This paper synthesizes results from two previously published studies (Oswalt and others 2007, Oswalt and Oswalt 2007) and, in addition, uses information from other pertinent literature with respect to the facilitation and impacts of *M. vimineum* invasions in Eastern hardwood forests. We also consider implications of the developing knowledge of *M. vimineum* invasions for timberland management within its currently known range. Lastly, we suggest modes of management that may aid in reducing the spread and impacts of this highly-invasive grass.

STUDY SITE

Both studies were conducted on The Ames Plantation in southwest TN in the headwaters region of the North Fork of the Wolf River (NFWR) (35°09´ N, 89°13´ W). Part of the Southeastern Mixed Forest Province (Bailey 1995), the site primarily is composed of mixed hardwood forest dominated by various oak species (*Quercus* sp.) and yellow-poplar (*Liriodendron tulipifera*). Historically, the study site was used for agriculture, grazing, and timber production. Surrounding properties include woodlands interspersed with soybean, cotton, and other agricultural crops common to the southeast.

METHODS

Microstegium vimineum Expansion Study

In late summer 2004, we identified and marked established *M. vimineum* patches for future relocation and plot/treatment installation. In December 2004, we established 40 plots (2 by 0.5 m) within 10 blocks of 2 replicates each (2 plots per replicate, 2 replicates per block). Each block comprised one established *M. vimineum* patch located beneath an undisturbed, closed hardwood canopy and controlled for slope and aspect. In addition, plots were selected to avoid large differences in initial leaf litter thickness. Plot installation resulted in each plot radiating 2 m out from the established *M. vimineum* patch with the 0.5-m face adjacent to the patch (fig. 1). One of two treatments was randomly assigned to each plot within a block. Treatments included a disturbed (litter removed) and undisturbed (no litter removed) litter layer. For the disturbed treatment all leaf litter was removed from the plot and special care was taken to leave the A horizon intact. Plots were visually marked in such a way as to minimize the chance of further anthropogenic disturbance. Linear spread and cover expansion from established *M. vimineum* patches were documented after one complete growing season—in the fall of 2005—for each plot. Linear spread was quantified by measuring the linear distance (meters) from the previously delineated boundary between the plot and established *M. vimineum* patch to the furthermost stem of *M. vimineum*. Cover expansion was quantified by estimating percent *M. vimineum* cover for each of four 0.5-m^2 subsections of the plot (fig. 2), defined as 0.0 to 0.5, 0.5 to 1.0, 1.0 to 1.5, and 1.5 to 2.0 m in progressive 0.5-m divisions from the established *M. vimineum* patch.

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Simple analysis of variance (ANOVA) was used to test for significant differences between treatments for linear spread and cover expansion with α of less than 0.05 used to indicate differences. Fisher's Least Significant Difference (LSD) tests were used for post-ANOVA mean separation (SAS Institute Inc. 1999). A simple one-sample t-test was used to test if the linear spread of the undisturbed plots was different from zero.

Microstegium vimineum Impact Study

In fall 2001, we identified three experimental blocks based on landform and position. Differences in average stand basal area were significant among the blocks (20-36 m^2/ha, *P* = 0.04), which appeared to be a result of past selective cutting. Twelve 0.8-ha treatment units (approximately 61 by 122 m) were evenly distributed within the experimental blocks. Three canopy disturbance treatments (0 m^2/ha or 0 percent residual canopy; 3.2 m^2/ha or 10 percent residual canopy; and 4.6 m^2/ha or 20 percent residual canopy) and an undisturbed control (32.6 m^2/ha or 100 percent residual canopy) were randomly assigned to the 4 units within each of the 3 replicate blocks using a randomized complete block design. Canopy disturbance treatments were completed in the winter of 2001–2002.

To evaluate the impacts of *M. vimineum* on woody regeneration density and species diversity, we recorded percent cover estimates for *M. vimineum* in late summer 2003 from 60 systematically located 1-m^2 plots in each unit, for a total of 720 plots. Native woody species regeneration in four height classes (< 0.61, 0.61 to 1.22, 1.22 to 1.83, and > 1.83 m) was quantified using a 0.0004-hae (1/1000-acre) plot nested within a 0.004-ha (1/100-acre) plot. We recorded six

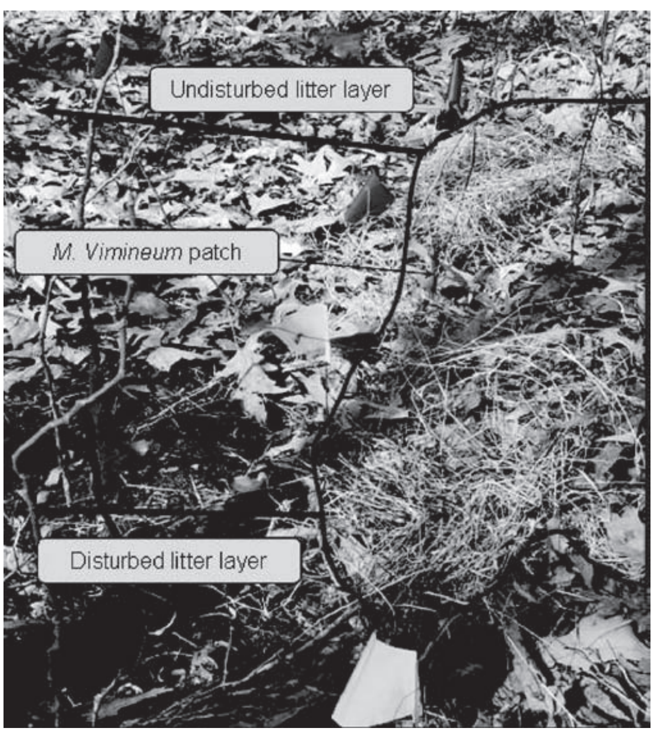

Figure 1—Undisturbed and disturbed litter layer treatments were aligned in transects adjacent to and leading away from previously established patches of *M. vimineum*.

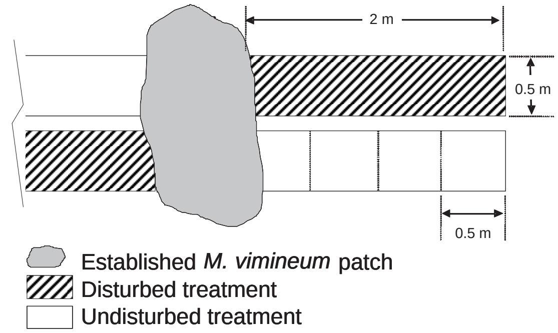

Figure 2—Plot layout illustration.

plots for each unit, for a total of 72 plots. Each regeneration plot was classified into one of four broad *M. vimineum* cover classes (less than 25, 25 to 50, 51 to 75, and greater than 75 percent) through spatial association with the *M. vimineum* plots.

Mixed-model analysis of variance and least square means were used to discern differences in native woody species (NWS) density (stems/ha) and NWS diversity among canopy disturbance levels (SAS Institute Inc. 1999). We compared total native woody species (NWS) density (stems/ha) among canopy disturbances, and across four height classes to ensure that the populations of comparison were similar. We then used polynomial regression to identify possible relationships and trends between total square-root transformed NWS stems/ha and mean *M. vimineum* cover.

Shannon's and Simpson's diversity indices, along with species richness, were used to quantify NWS diversity. To ensure that treatment was not a covariant factor in NWS diversity regression models, we compared species richness among three canopy treatments (no control) using ANOVA. We then used simple linear regression to identify possible trends and relationships between diversity and mean *M. vimineum* cover across two diversity indices (Shannon's H and Simpson's D). Further, we used protected, one-way analysis of variance (Tukey's studentized range test) to control for Type I experiment-wise error and to detect differences in both NWS density and diversity (Shannon's and Simpson's indices and species richness) among broad *M. vimineum* cover classes.

RESULTS

M. vimineum Expansion Study

Plots receiving the disturbed treatment experienced *M. vimineum* spread 4.5 times greater than plots receiving the undisturbed treatment (fig. 3, P < 0.0001). Linear spread averaged 1.66 and 0.37 m for the disturbed and undisturbed treatments, respectively. While mean *M. vimineum* cover decreased significantly as subsection distance from the established plot increased for both the undisturbed and disturbed plots, *M. vimineum* cover was significantly greater for each subsection within the disturbed plots (P < 0.001) (fig. 4). *M. vimineum* cover averaged 16, 4, 0, and 0 percent for the undisturbed treatment and 87, 64, 31, and 9 percent for the disturbed treatment in the 0.0 to 0.5, 0.5 to 1.0, 1.0 to 1.5, and 1.5 to 2.0 m subsections, respectively.

M. vimineum Impact Study

Regression models with *M. vimineum* percent cover as the independent variable indicated a strong negative relationship with total NWS stems/ha (r^2=0.80, slope=-1.1, P<0.001). Regression models also indicated that *M. vimineum* may have had a greater influence on the smaller height classes. The coefficient of determination was larger and its associated p-value smaller for height class 1 (r^2=0.82, P<0.0001). Progressing through larger height classes resulted in decreasing R^2 values and increasing p-values, until significant relationships no longer existed for the largest seedling height class (r^2=0.70, P<0.0001, r^2=0.50, P=0.002, r^2=0.16, P<0.11 for HC2, HC3 and HC4, respectively). Native woody species density (total stems/ha) differed among the four broad *M. vimineum* cover classes (P=0.0004) (table 1). The > 75 percent cover class resulted in significantly fewer stems/ha than both the < 25 percent and the 25 to 50 percent cover classes.

Simple linear regression using Shannon's H diversity index as the dependent variable, and mean percent cover of *M. vimineum* as the independent variable produced an R^2 value of 0.47, and a slope of -0.007 (P=0.002). Re-running this model using Simpson's D diversity index showed a weak negative relationship (r^2 = 0.31, slope = -0.02, P=0.02). Both species richness and Shannon's H diversity index differed among the broad *M. vimineum* cover classes (P=0.0002 and P=0.01, respectively) (table 1). Similar to the regression analysis, ANOVA results indicate that species richness consistently declined with progressively increasing *M. vimineum* percent cover. Differences are particularly noticeable between the < 25 and > 75 percent cover classes. Differences in Shannon's H among the broad cover classes include only a difference between the < 25 and > 75 percent classes (table 1).

DISCUSSION AND IMPLICATIONS

M. vimineum is an invasive species in southern forests that is gaining the attention of land managers. Two studies conducted in southwest TN suggest that, when *M vimineum* is present at a site prior to manipulation, winter litter disturbance and canopy disturbance can encourage the spread and growth of the species. The end result may be an overall decline in native woody species regeneration success. Logging operations or silvicultural treatments in the southern United States often result in what can be labeled a planned disturbance. The presence of heavy machinery of most logging operations can result in extensive disturbance to the forest floor litter layer (Buckley and Marshall 2005). If *M. vimineum* is present and left untreated prior to litter disturbance, site manipulation may further encourage its spread and establishment. Likewise, if *M. vimineum* is present in the understory prior to canopy removal, harvest may result in excessive growth and therefore negatively impact regeneration. While logging operations are not the only facilitator of *M. vimineum* spread, and other disturbances probably are influencing the species' growth, knowledgeable land managers should recognize the impact of this invasive grass and attempt to slow its spread.

Land managers in states where *M vimineum* is present would benefit by taking note of whether the plant is present in or adjacent to their forests where site manipulation is expected. Current research indicates that *M. vimineum* can be treated in the late fall and winter with a pre-emergence herbicide and then again after the first growth flush in the spring with a post-emergence, grass-specific herbicide (Miller 2003). A challenge is presented by the fact that extirpating *M. vimineum* from a site may take more than one year because of a large seed bank.

Land managers, foresters, and loggers should be made aware of the potential impact and range of *M. vimineum* invasions. Managing an identified population before a natural or planned disturbance should limit both the spread

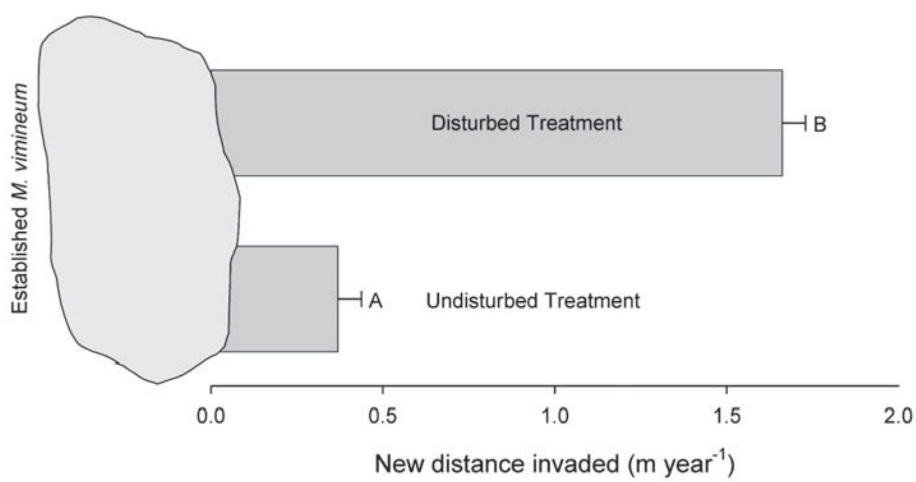

Figure 3—Mean linear distance invaded by *M. vimineum* for the disturbed and undisturbed treatments. Lettering indicates differences (P < 0.0001) between treatments.

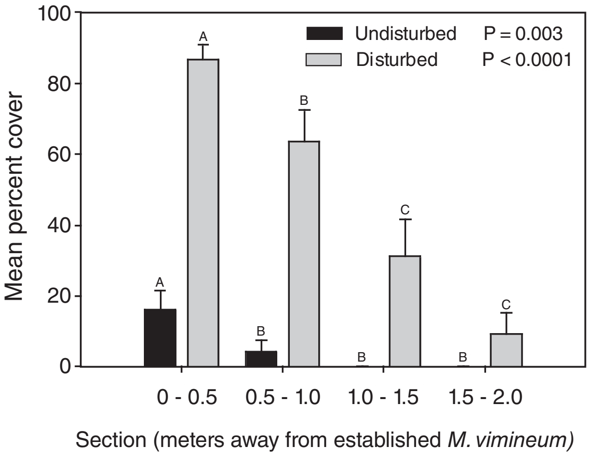

Figure 4—Mean percent cover of *M. vimineum* in each of four measured plot sections for the disturbed and undisturbed treatments. Lettering is used to indicate differences within a treatment.

of *M. vimineum* through leaf litter displacement and the subsequent negative impacts on the density and diversity of native woody species. A proactive management approach may lessen the impact of this invasive grass.

ACKNOWLEDGMENTS

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Table 1—Mean density, species richness and Shannon's H diversity index for each of four broad *M. vimineum* cover classes

Broad cover class	Density		Richness		Shannon's H	
percent	Stems/ha	se	Species/plot	se		se
Less than 25	36412 [A]	5554	15.7 [A]	1.1	1.93 [A]	0.08
25 to 50	28911 [AB]	1236	13 [AB]	2	1.96 [AB]	0.15
51 to 75	6425 [BC]	2718	9.5 [BC]	1.5	1.87 [AB]	0.21
Greater than 75	4098 [C]	1043	6.3 [C]	0.9	1.38 [B]	0.12

Lettering indicates differences among cover classes.

INFLUENCING FACTORS ON VEGETATIVE COGONGRASS SPREAD INTO PINE FORESTS ON THE MISSISSIPPI GULF COAST

Jon D. Prevost, Donald L. Grebner, Jeanne C. Jones, Stephen C. Grado, Keith L. Belli, and John D. Byrd[1]

Abstract—Cogongrass [*Imperata cylindrica* (L.) Beauv.] is an invasive species that is spreading throughout forested ecosystems across the Southeastern United States. A field experiment was conducted in Hancock County, MS to determine if mid-rotation mechanical disturbance increased the rate of growth and spread of roadside cogongrass patches into adjacent forest stands. Logging disturbance was replicated on 18 treatment sites using a 65 horsepower New Holland tractor and a box blade. The distance of linear spread and tiller growth into adjacent forest stands was measured during and after the growing season following disturbance. Comparisons were made between disturbed and undisturbed sites. Cogongrass exhibited significantly higher rates of spread in disturbed sites versus undisturbed sites and rhizome biomass was strongly related to this process.

INTRODUCTION

Cogongrass (*Imperata cylindrica* (L.) Beauv.) is a non-native invasive that has been invading southern forests for nearly a century. Introduced in the winter of 1911-1912 as packing material for a crate of oranges, cogongrass has spread from the site of original introduction and covered thousands of forested acres in the Southeastern United States (Tabor 1952). Cogongrass is a warm season, rhizomatous, perennial grass native to Southeast Asia (Holm and others 1977). The negative impacts of cogongrass are numerous and include the exclusion of native vegetation, altered natural fire regimes, degraded wildlife habitat, and difficult regeneration of southern pine (Dozier and others 1998, Ramsey and others 2003).

Cogongrass forms dense monotypic patches void of most forms of native vegetation. Arising from an extensive rhizome system that can reach 16 tons per acre of below ground biomass, tillers reach average heights of 0.5 to 4 feet (Holm and others 1977). One to four leaves will branch off each tiller becoming progressively shorter upwards on the tiller. Leaves are approximately 0.5 inches wide with raised scabrous margins and a white offset midrib (Bryson and Carter 1993, Dozier and others 1998).

Spreading by seed and rhizome, each method presents notable challenges to forest managers and landowners. Cogongrass seed heads contain up to 3,000 wind disseminated seeds that must contact bare mineral soil for germination to occur (Shilling 1997). The tufted inflorescences travel an average of 49 feet, although much longer distances have been reported (Holm and others 1977). Vegetative spread by rhizome is also a significant concern. The introduction and spread of cogongrass throughout MS and FL has been primarily attributed to the use and transportation of contaminated fill material (Patterson and McWhorter 1983, Willard 1988). Cogongrass has also spread by rhizome movement from established patches by blades, discs, mowers, grapples, tires and other pieces of machinery (Dozier and others 1998, Willard 1988). Only 0.0035 ounces of rhizome are required for successful establishment of a cogongrass plant (Soerjani and Soemartwoto 1969). Rhizome pieces have been documented to spread up to 172 square feet and produce 350 shoots in 11 weeks (Eussen 1980).

The ability of cogongrass to reproduce and spread in a forested setting may depend on current and past management activities. Disturbances that displace and disturb the litter layer and underlying soil such as mechanical thinning, harvesting, burning, and herbicide and fertilizer application can create conditions conducive to the growth and spread of cogongrass (Holm and others 1977). Holm and others (1977) also recognized the concept of dense shrub and herbaceous cover acting as a forest barrier preventing cogongrass invasion. Driving or operating machinery within a forest stand disturbs the shrub and herbaceous layers creating “pathways” for cogongrass to enter. What remains unknown is the extent that disturbances increase growth and spread rates of cogongrass and what specific factors influence these rates. This study assessed the change in growth and spread rates following a simulated logging disturbance and also considered multiple influencing factors.

METHODS

To test the hypothesis that logging disturbance increases the rate of cogongrass spread, 18 roadside cogongrass plots were chosen to receive a simulated logging disturbance treatment, while an additional 18 plots were chosen for control. Criteria for plot selection were developed to avoid physical obstructions (i.e., deep ditches) and to prevent variation in data due to factors such as standing water, low understory density, and open canopy. Logging disturbance was simulated by dragging a 5-foot box blade through each 12 by 30 foot treatment plot with a 65 horsepower New Holland tractor until the disturbance resembled that of an actual disturbance created by dragging felled timber to the roadside using conventional skidding methods. Initial measurements were taken in February 2006 and included distance from an established baseline to furthest cogongrass tiller and number of tillers in a 3 by 10 foot sub-plot. Subsequent measurements were taken in November

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2006 after one growing season. Mean growth and spread rates were tested for significance using one-way ANOVA (α = 0.05), and related factors were identified using simple linear regression.

RESULTS

The rate of cogongrass spread in disturbed plots was significantly greater ($p = 0.0127$) with an average of 45.5 inches while control plots averaged 10.6 inches (fig. 1). The number of new cogongrass tillers in disturbed plots (53.4 tillers) was also significantly ($p = 0.0018$) higher than in control plots (8.9 tillers) (fig. 2). November 2006 measurements indicated a maximum gain of 203 tillers, and over 13 feet of spread in particular disturbed plots after one growing season. Using simple linear regression, the only strong linear relationship ($p \leq 0.0001$) observed was between cogongrass tiller growth and rhizome biomass with an R^2 value of 0.81.

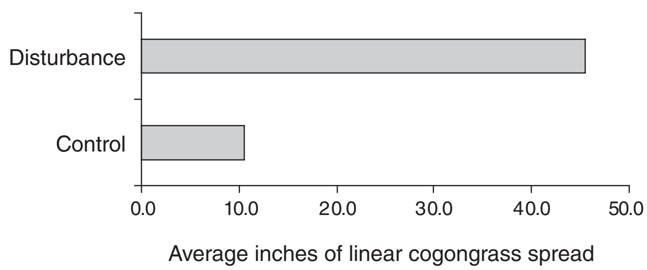

Figure 1—Average inches of linear cogongrass spread into a forest Stand in disturbed and control plots after one growing season following a simulated logging disturbance at John C. Stennis Space Center in Hancock County, MS during 2006.

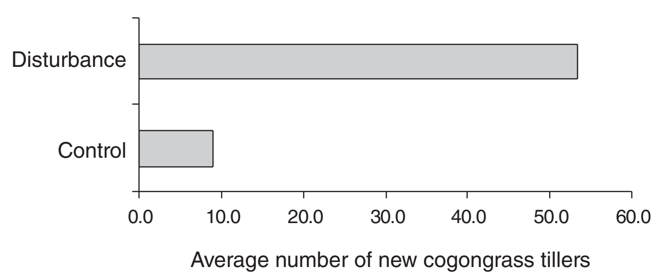

Figure 2—Average number of new cogongrass tillers in disturbed and control cogongrass plots after one growing season following a simulated logging disturbance at John C. Stennis Space Center in Hancock County, MS during 2006.

DISCUSSION AND CONCLUSIONS

This study showed that disturbance related to certain forest management activities, such as a logging disturbance, increased the growth and spread rates of roadside cogongrass patches into an adjacent forest stand. To control the spread of cogongrass, managers and landowners must take action to minimize or reduce disturbance in or around cogongrass patches, or by gaining control of cogongrass with herbicide applications in areas where disturbance is unavoidable. Additionally, buffer strips of dense shrubs should be left intact where cogongrass patches adjoin the forest stand. Protecting the integrity of these buffers can potentially reduce spread by increasing light competition and by slowing wind speeds limiting the travel distance of cogongrass seeds. Results of this study also indicated that rhizome biomass was the primary influencing factor behind the growth of cogongrass on sites disturbed similar to that of a logging disturbance. The positive correlation between rhizome biomass and tiller growth indicated that although above ground spread into adjacent forest stands may not be obvious, underground rhizomes were spreading into the stand and waiting on some disturbance to encourage foliar growth. Given that most rhizome mass was contained in the upper soil strata, deeper disturbances increase the odds of rhizomes being displaced and producing new plants farther into the forest.

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EFFECTS OF MECHANICAL AND CHEMICAL CONTROL ON *MICROSTEGIUM VIMINEUM* AND ITS ASSOCIATES IN CENTRAL WEST VIRGINIA

Jonathan Pomp, Dave McGill, William Grafton, Rakesh Chandran, and Russ Richardson[1]

Abstract—Various studies have identified methods for effectively controlling Japanese stilt grass [*Microstegium vimineum* (Trin.) A. Camus]. However, the effect of *M. vimineum* control treatments on native flora has not been documented. This is of particular interest because an effective *M. vimineum* control method that minimizes impact on native vegetation should be considered the most desirable technique. This study investigates the effects of various control treatments on *M. vimineum*, and the associated native understory community, on an upland and bottomland hardwood site in central WV (38°46' 08"N, 81°03' 52"W). Control treatments examined in the study included: a low-volume glyphosate application (6 ounces per acre); both a single (early June) application and a double application (early June and August) of fenoxaprop-p-ethyl (13 ounces per acre); and mechanical control (weed whip). In the first growing season following the treatments, single applications of fenoxaprop-p-ethyl provided greater than 95 percent control of *M. vimineum* at both sites. Mechanical control also proved to be very effective. In addition to showing an increase in species diversity, fenoxaprop-p-ethyl treated plots also exhibited post-treatment species richness values that were significantly higher than all other treatments ($P < 0.05$). The results of this study suggest that this selective herbicide has the potential to be used to restore native plant communities in *M. vimineum* infested areas of mixed hardwood forests.

INTRODUCTION

Invasions by alien plants are a growing challenge worldwide to the management of native biodiversity and ecosystem functioning (Brooks and others 2004, Gordon 1998, Steele and others 2006). In mixed deciduous hardwood forests of the eastern United States, invasive shrubs, vines, trees, and grasses are threatening native flora, as well as the habitats that they compose. Of particular importance, in WV and throughout the central Appalachians, is the impact of Japanese stilt grass [*Microstegium vimineum* (Trin.) A. Camus] on forest reproduction and economically valuable herbaceous plant communities, e.g., American ginseng (*Panax quinquefolius* L.), goldenseal (*Hydrastis canadensis* L.), and black cohosh [*Cimicifuga racemosa* (L.) Nutt.]. Once established, *M. vimineum* is capable of crowding out native herbaceous vegetation in wetlands and forests within three to five years (Barden 1987, Hunt and Zaremba 1992). Despite not being listed on the United States Department of Agriculture invasive and noxious weeds list for WV, some feel that Japanese stilt grass should be considered as the state's greatest threat to native forest understory habitat (WVDNR 2006).

M. vimineum, also commonly referred to as stilt grass, annual jewgrass, wire grass, Nepalese browntop, and Chinese packing grass, is a shade tolerant C_4 annual grass of Asiatic origin. The exotic grass was introduced into the United States in 1919 in Knoxville, TN (Fairbrothers and Gray 1972). Placed in an environment with no natural enemies, the aggressive grass readily reproduced and began to disseminate. Today, it is widely distributed in dense patches on river banks, flood plains, damp fields, swamps, lawns, woodland thickets, logging roads, and roadsides throughout the eastern United States (Barden 1987, Cole and Weltzin 2005, Fairbrothers and Gray 1972).

M. vimineum possesses several traits that contribute to its competitive and invasive nature. The grass shows a very plastic response to varying habitat conditions (Claridge and Franklin 2002, Gibson and others 2002, Tu 2000, Winter and others 1992). For example, *M. vimineuem*, like all C_4 plants, prefers moderate to high light levels for reproduction, dispersal, and establishment, however, *M. vimineum* can grow, reproduce, and disperse seed in only five percent full sunlight (Winter and others 1992). *M. vimineum* has also been reported to promote positive feedback processes with the soil, further enhancing its ability to spread (Gibson and others 2002, Kourtev and others 1998, Tu 2000). The exotic invasive grass also possesses a persistent seed bank that remains viable for three to seven years (Barden 1987, Gibson and others 2002, Tu 2000). *M. vimineum* is slow to invade undisturbed areas; however disturbance (natural or anthropogenic) favors the establishment of the species (Barden 1987, Oswalt and others 2007, Tu 2000). In West Virginia, *M. vimineum* populations are especially abundant on logging roads and forest edges following operations that disturb the soil and/or forest canopy.

Various studies have identified methods for effectively controlling *M. vimineum*. It should be noted that early control of source populations at forest edges is likely a more effective strategy than concentrating on patches within a forest interior (Cole and Weltzin 2004, Cole and Weltzin 2005, Huebner 2006). The preferred control method is removal of the plant by hand pulling late in the growing season before seed production and after seed set of most co-associates (Gibson and others 2002, Tu 2000). This method provides minimal environmental impact, but is very labor and time intensive, especially when dealing with large populations. Mechanical removal, using a "weed whacker," or "weed eater," also works

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well late in the growing season (Gibson and others 2002, Tu 2000), and is much less labor and time intensive.

Post-emergence herbicides have also been proven effective, and may be the only choice for large infestations. Based on research at the University of Tennessee, the Nature Conservancy recommends using imazapic, fluazipop-P, and glyphosate (Tu 2000). In addition, other research supports the effectiveness of clethodim, fenoxaprop-P, sethoxydim, and glufosinate, (Gover and others 2003, Judge and others 2005a). A preliminary study by Judge and others (2005a) found that double applications of clethodim, fenoxaprop-P, sethoxydim, and glufosinate controlled >90 percent of containerized *M. vimineum* in VA and NC. A single application of glyphosate also provided adequate control. A follow up study by Judge and others (2005b) found that single applications of fenoxaprop-P, imazapic, and sethoxydim controlled *M. vimineum* 83 to 89 percent in both a mixed pine-hardwood and hardwood forest. Seedling emergence in the second growing season following the treatment was reduced 78 to 89 percent (Judge and others 2005b). This study also showed that double applications (four weeks apart), at half the registered rate, were effective (Judge and others 2005b). Herbicide research, however, is limited to these few studies, and is nonexistent in WV. More importantly, the effect of *M. vimineum* control treatments on native understory communities has not been documented. This is of particular interest because an effective *M. vimineum* control method that minimizes impact on native vegetation should be considered the most desirable technique.

This article focuses on the effects of various control treatments on Japanese stilt grass, and the associated native understory community, on an upland hardwood and bottomland hardwood site in central WV. Treatments examined include: a low-volume glyphosate (tradename Accord) application (6 ounces per acre); both a single (early June) application and a double application (early June and August) of fenoxaprop-p-ethyl (tradename Acclaim Extra) (13 ounces per acre); and mechanical control (weed whip). Treatment effects are described for the first growing season following the treatments. Two research questions will be answered, including: (1) what is the efficacy of each treatment for controlling *M. vimineum*? and (2) how does each treatment effect species richness and diversity of the associated understory stratum? The information presented should help foresters and other land managers to better understand how *M. vimineum* control treatments might affect understory species composition and dynamics in the Central Hardwood Region.

METHODS

Study Site

The experiment was conducted in 2006 in established stands of *M. vimineum* on both upland and bottomland hardwood sites. Both sites are located in eastern Calhoun County, WV (38°46’ 08”N, 81°03’ 52”W), within the Right Fork of Crummies Creek watershed. The area is characterized by average annual precipitation of 42 inches, an average annual temperature of 53.6 ºF, and a growing season of approximately 159 days (Pate 1999). Braun (1950) characterized the area as being part of the mixed mesophytic cover type.

The upland site was selected to focus on treatment effects on the native understory community. This site is located on a skid road on an east-facing slope at an elevation of 1,065 feet. The area was impacted by an ice storm in 1994, and a salvage operation occurred the following year. *M. vimineum* quickly established following the disturbance, and currently encompasses, on average, 58.93 percent of the understory cover along the corridor.

The overstory of the hardwood forest at this site is composed primarily of typical cove hardwood species, including; sugar maple (*Acer saccharum* Marsh.), yellow-poplar (*Liriodendron tulipifera* L.), basswood (*Tilia americana* L.), and hickories (*Carya spp*.). The soil type is of the Gilpin-Peabody complex. These soils are very steep, well drained silt loams. Erosion has removed most of the original surface layer of these soils, and in places the subsoil is exposed (Pate 1999).

The bottomland site was selected to focus on treatment effects on *M. vimineum*. The area is located at an elevation of 821 feet in a valley bottom. The site is located within the floodplain of the Right Fork of Crummies Creek, a small perennial stream. *M. vimineum* has been established in this area since the mid 1990s as well. Here, *M. vimineum* composes, on average, 70.68 percent of the understory cover.

Canopy cover is minimal at the bottomland site and yellow-poplar, slippery elm (*Ulmus rubra* Muhl.), American sycamore (*Platanus occidentalis* L.), and black walnut (*Juglans nigra* L.) are the main species mix. The soil type is known as Sensabaugh silt loam. This soil is nearly level, very deep, well drained, and is subject to occasional flooding (Pate 1999).

Field Methods

Fifteen treatment plots were established at each site. At the upland site, 0.001-acre circular plots, having 3.72 feet radius, were established along the skid road. Plots were placed no closer that 15 feet apart, and percent cover, by species, was visually estimated. Rectangular plots, measuring 23 by 5 feet, were established at the bottomland site. Here plots were inventoried using the point-intercept method (Caratti 2006). Measurements were made at systematic 2-foot intervals, for a total of 20 measurement points per plot. “Hits” were tallied into one of four categories, including; Japanese stilt grass, other grass species, herbaceous species, and woody species. Both sites were inventoried prior to treatment (June), and again in early August and October 2006.

Four treatments were examined, including; a low-volume glyphosate (tradename Accord) application, both a single application and a double application of fenoxaprop-p-ethyl (tradename Acclaim Extra), and mechanical control (weed whip). The glyphosate, a non-selective post-emergence herbicide, was applied at a rate of 6 ounces per acre. This rate is commonly used by Christmas tree growers to stunt grasses to make it easier for customers to walk down rows between trees. Fenoxaprop-p-ethyl, on the other hand, is a selective post-emergence herbicide designed only to kill monocots. Both the single and double applications of this herbicide were applied at the registered rate (13 ounces per acre).

All treatments, and a control (or check), were randomly assigned to plots at both sites (three replicates). Chemical treatments were applied on June 6. The second fenoxaprop-p-ethyl applications, and the mechanical treatment, were applied on August 11 and 15, respectively. Herbicides were applied using a CO_2-pressurized backpack sprayer equipped with a 5 foot boom and 4 fan nozzles. The sprayer was calibrated to deliver 27.76 gallons per acre.

Analytical Methods

Pre and post-treatment percent cover data were arcsine transformed for both sites, and *M. vimineum* control was quantified by the percentage change in these values. Percentage change was calculated by subtracting pretreatment values from post-treatment values, dividing by pretreatment values, and multiplying the quotient by 100. Upland site species richness, or the count of a number of different species, was also evaluated for both pre and post-treatment data. Species diversity was quantified, for the upland site, for both pre and post-treatment data using Simpson's Diversity Index (SDI) (Simpson 1949). With SDI, species diversity can range from zero to one with values closer to zero representing higher diversity. This is sometimes a bit confusing, so all SDI values were subtracted from one. This made the results less puzzling by making higher SDI values represent higher diversity.

All statistical analyses were performed using SAS 9.1 software (SAS Institute, 2003), with significance determined at $\alpha \leq 0.05$. Treatment effects on percentage change in *M. vimineum* cover, species richness, and species diversity were assessed using a General Linear Model (GLM) procedure. Mean comparisons were evaluated using Fisher's protected Least Significant Difference (LSD) test (t-test). The null hypothesis of the study (H_0) was that there was no difference in dependent variables across treatments.

RESULTS AND DISCUSSION

***M. vimineum* Control**

Both single (Acclaim 1) and double applications (Acclaim 2) of fenoxaprop-p-ethyl, as well as the weed whip treatment, provided, on average, greater than 97 percent control of *M. vimineum* at the upland site (fig. 1). These three treatments were significantly different from both the glyphosate treatment and the untreated plots. These findings were comparable to those of the experiments conducted by Judge and others (2005a) and Judge and others (2005b). Glyphosate provided, on average, only a 23 percent reduction in *M. vimineum* cover. On untreated plots, *M. vimineum* cover increased by an average of 44 percent.

Results at the bottomland site were somewhat similar. Once again, both a single application of fenoxaprop-p-ethyl and the weed whip treatment provided adequate control of *M. vimineum*. These two treatments were significantly different from both glyphosate treated plots and untreated plots. They were, however, not significantly different from the double application of fenoxaprop-p-ethyl, which only provided, on average, a 54 percent reduction at this site (fig. 2). The glyphosate treatment caused only a minute decrease (2 percent on average) in *M. vimineum* cover, and again, *M. vimineum* cover increased quite dramatically on untreated plots.

The ineffectiveness of the glyphosate treatments, at both the bottomland and upland sites, disagrees with other published

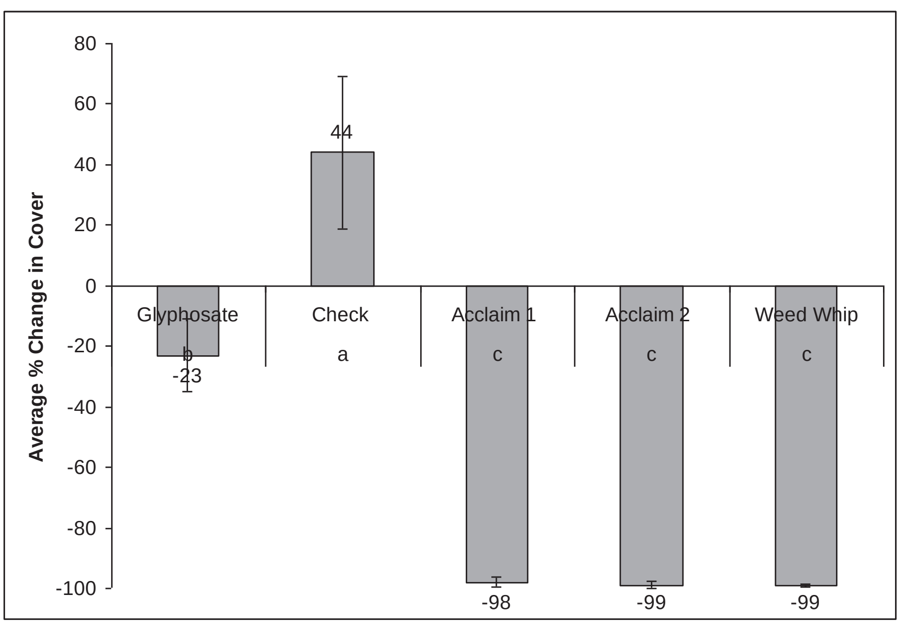

Figure 1—Average percent change in *M. vimineum* cover by treatment: upland site. Means with the same letter are not significantly different at $\alpha \leq 0.05$. Error bars represent +/- one standard error.

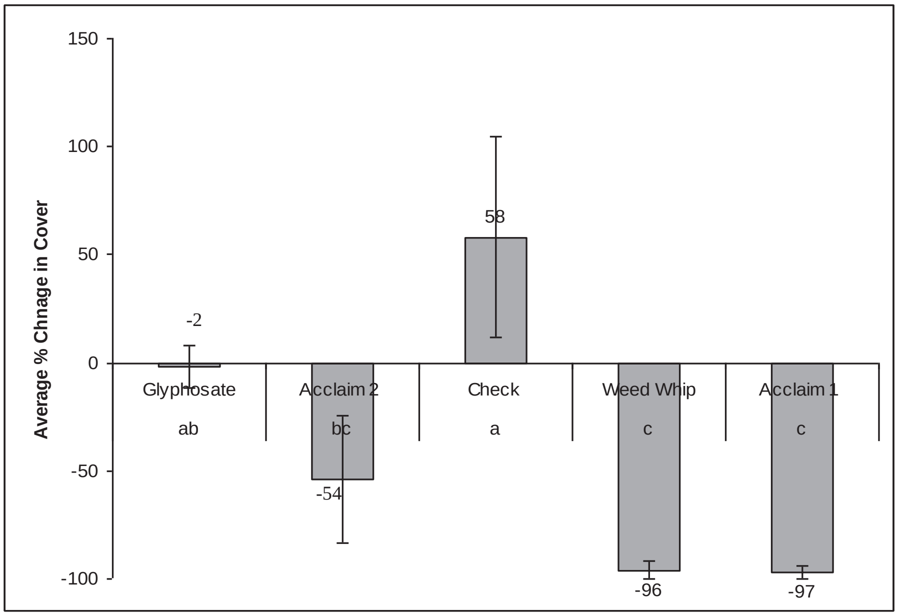

Figure 2—Average percent change in *M. vimineum* cover by treatment: bottomland site. Means with the same letter are not significantly different at $\alpha \leq 0.05$. Error bars represent +/- one standard error.

studies. It should be noted, however, that, in this study, glyphosate was applied at about 1/5 the rate of other studies. Also, two of the glyphosate treated plots at the upland site were not completely covered when sprayed. That is, 1/2 of those plots were missed by the sprayer. This fact certainly caused some bias in the results and glyphosate, therefore, can not be ruled out as having the potential to be an effective management tool.

Species Richness

In June, species richness ranged, on average, from 12 to 16 at the upland site. At this time, the values were not significantly different between treatment plots. In August, species richness values were still quite similar, and ranged from 11 to 16. Again, these values were not significantly different at $\alpha \leq 0.05$. By October, however, a noteworthy difference was observed (fig. 3).

Here, species richness ranged from 8 to 17, and plots that were treated with both single and double applications of fenoxaprop-p-ethyl showed average species richness values that were significantly higher than the glyphosate, weed whip, and untreated plots. Much like the findings of Oswalt and others (2007), where *M. vimineum* cover increased (untreated plots) species richness decreased (16 species in June to eight species in October). Plots that were treated with both single and double applications of fenoxaprop-p-ethyl contained 17 and 15 different species, respectively.

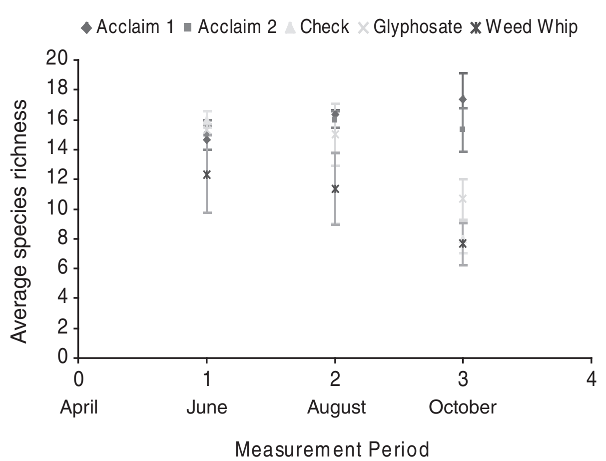

Figure 3—Average species richness by treatment and measurement period. Error bars represent +/- one standard error.

Table 1—Most frequently encountered species: upland site

Rank[a]	Common name	Scientific name
1	Sugar maple	*Acer saccharum* Marsh.
2	Fall fescue	*Festuca spp.*
3	White snake root	*Eupatorium rugosum* Houtt.
4	Jack-in-the-pulpit	*Arisaema triphyllum* (L.) Schott
5	False nettle	*Boehmeria cylindrica* (L.) Sw.
6	White grass	*Leersia virginica* Willd.
7	Large yellow wood sorrel	*Oxalis europaea*
8	Aborted buttercup	*Ranunculus aborvitus*
9	Hairy bittercress	*Cardamine hirsuta* L.
10	Spicebush	*Lindera benzoin* (L.) Blume

[a]Rank is based on frequency of occurrence in study plots.

Table 1 lists the ten most frequently encountered species at the upland site (post-treatment). These are, however, only a fraction of what was actually encountered. In addition to these species, we came across an astounding 77 other herbaceous, grass, and woody species; indicating a high potential for restoration of native plant communities in *M. vimineum* infested areas.

Species Diversity

Figure 4 shows average species diversity before and after treatments. Treatments are arranged from smallest change to largest change, reading left to right. Plots that received both single and double applications of fenoxaprop-p-ethyl, as well as the weed whip treatment, experienced an increase in species diversity from pretreatment to post-treatment (fig. 4). The change in species diversity for these three treatments was significantly different from untreated plots at $\alpha \leq 0.05$.

Both the single application fenoxaprop-p-ethyl and weed whip treatments were also significantly different from the plots treated with glyphosate. Both glyphosate treated, and untreated, plots resulted in decreased species diversity. The weed whip results, however, may be a bit misleading because species diversity is relative to the amount of cover. Post-treatment percent cover on weed whip plots averaged only 10.3 percent, compared to 46 and 47.3 percent on the single and double application fenoxaprop-p-ethyl plots. Examination of mechanical treatments over multiple growing seasons would limit bias and likely produce more indicative results.

Compositional Trends: Bottomland Site

Despite the lack of species richness and diversity data, a few compositional trends could still be noted at the bottomland site. In general, as *M. vimineum* cover increased, native understory

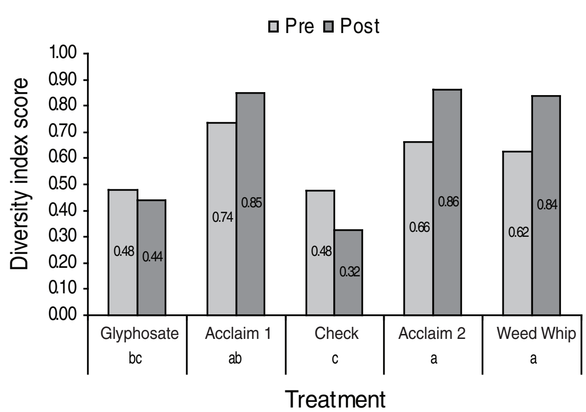

Figure 4—Pre-treatment vs. Post-treatment Diversity Indices. Treatments with the same letter are not significantly different at $\alpha \leq 0.05$.

Table 2—Average percent change in cover (pre- to post-treatment) by species group and treatment: bottomland site

Species Group	------------ Treatment ------------				
	Acclaim 1	Acclaim 2	Check	Glyphosate	Weed Whip
M. vimineum	-97 c	-54 bc	58 a	-2 ab	-96 c
Herbaceous	17 a	0 ab	-58 c	-30 bc	-15 ab
Other Grass Spp.	21 a	4 ab	-22 ab	-39 b	-22 ab

For each species group, means with the same letter are not significantly different at $\alpha \leq 0.05$.

flora decreased and vice versa. Herbaceous and other grass species percent cover increased on plots treated with a single application of Acclaim (table 2). Native flora experienced only a minute change on plots treated with two Acclaim applications. Native herbaceous and grass species decreased on untreated, as well as, glyphosate and weed whip treated plots. It should be noted that woody species were not included in the analysis because so few were present on the plots.

CONCLUSIONS

Our results indicate that if *M. vimineum* is left untreated, it will readily out-compete native understory vegetation and begin to dominate a site. These finding are consistent with those of Barden (1987) and Oswalt and others (2007).

The results also point out a single application of Acclaim Extra, or fenoxaprop-p-ethyl, as being the best choice for controlling *M. vimineum* populations, and maintaining native understory flora in mixed hardwood stands of West Virginia. A double application of the chemical is unnecessary and will only cost the land manager more time and money. Mechanical control also proved to be very effective; again, however, the effects of this treatment on native vegetation need to be examined for more than a single growing season.

However, more research is needed on this topic for it to be fully understood. The effects of different selective herbicides on native vegetation should be examined. This study only compared selective and non-selective. Again, effects should be monitored over multiple growing seasons as well. A cost evaluation, for controlling both small and large infestations would also be very useful, especially for private landowners. Finally, it needs to be determined if biological control is a possibility. Pathogens, insects, and viruses have been proven to be effective for controlling other exotic organisms, and could be the missing link to widespread control of the aggressive, non-native, grass *M. vimineum*.

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COMPARISON OF ALTNERATIVE KUDZU CONTROL MEASURES ON A BEFORE-TAX BASIS IN MISSISSIPPI

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Abstract—Kudzu [*Pueraria montana* var. *lobata* (Willd.)] was initially planted in the Southern United States for a variety of uses. Changing land use and homestead abandonment over time has lead to the spread of kudzu across the countryside. The species may now be considered as the original invasive exotic species in the South. Currently, it is believed that kudzu covers more than seven million acres which prevents uses such as timber production and establishment of carbon plantations. Landowners wanting to reclaim these occupied sites need information that examines the biological and economic tradeoffs of alternative control measures. Using data collected on sites in MS, this study examines the financial tradeoffs of controlling kudzu using different herbicide regimes applied by a ground dispersion unit. This analysis is done on a before-tax basis using standard financial criteria. The results suggest that the most cost-effective way to control kudzu patches is to spray using Escort XP regardless of patch age.

INTRODUCTION

Kudzu is a rapid growing, trailing or climbing, semi-woody vine native to Japan, China, Taiwan, and India. It has been used in its native range for medicinal purposes, fiber production, and food for more than 2000 years. Kudzu was first introduced to the United States in 1876 as an ornamental vine at the Philadelphia Centennial Exposition (Shurtleff and Aoyagi 1977, Everest and others 1991, Mitich 2000). Farmers became interested in the vine's forage and grazing potential and by the early 1900s it was available through mail order catalogs (Everest and others 1991, Britton and others 2002). The Soil Conservation Service began promoting kudzu as a means of erosion control for many of the abandoned farms of the South in the 1930s. Approximately 85 million kudzu seedlings were planted by farmers and the Civilian Conservation Corps on about three million acres by 1946 (Everest and others 1991). By 1970, the U.S. Department of Agriculture listed kudzu as a weed and in 1997 Congress voted in favor of adding it to the Federal Noxious Weed List (Miller and Edwards 1983, Everest and others 1991).

Current distribution of kudzu extends from eastern TX and OK to the east coast and as far north as VA and MD. However, the most heavily infested areas are in MS, AL, and GA. The goal of this study is to evaluate the financial returns on before-tax basis alternative management regimes that control kudzu and afforest sites into pine plantations for Mississippi. This information will be useful to landowners interested in evaluating the monetary tradeoffs of different approaches to controlling kudzu.

BACKGROUND

Kudzu vines have been reported growing up to 60 feet in a season and up to 12 inches of growth on a single summer day (Shurtleff and Aoyagi 1977, Everest and others 1991). Roots are woody and quite large reaching sizes of 8 feet in length, 12 inches in width, and weighing up to 400 pounds (Miller and Edwards 1983). Kudzu vines emerge from a root crown into woody stems that can grow to be 0.98 inches thick in 1 to 2 years. Some old vines have reached diameters up to 3.94 inches. Kudzu can grow and flourish across a wide range of soil types, but it grows best on deep, loamy soils (Everest and others 1991). It can also withstand a wide range of climatic conditions, but it excels in areas with over 39.37 inches of rainfall annually, long growing seasons, warm to hot summers, and mild winters (Shurtleff and Aoyagi 1977).

The aggressive nature of kudzu has caused it to shift from a possible forage crop and means of erosion control to a serious pest and invader of forests, lawns, pastures, and utility rights-of-way. Kudzu out-competes and overtakes practically all vegetation around it, including large trees. As it climbs its way up saplings and trees, kudzu winds around limbs reducing the amount of available sunlight, and may eventually result in death in 2 to 3 years (Mitich 2000, Britton and others 2002). Although no exact figures are known, Mitich (2000) estimates the economic loss due to kudzu encroachment to be in the hundreds of thousands of dollars. Beckwith and Dangerfield (1996) estimate annual losses in forest productivity of $7.85 per acre per year. Kudzu also climbs power poles, guy wires, and electrical lines where it can cause damage through electrical shorts and even the pulling down of the pole (Shurtleff and Aoyagi 1977). According to Britton and others (2002), Dr. James Miller estimated control costs by power companies alone to be around $1.5 million per year.

Kudzu is very difficult to control due to both its extensive root and rhizome system and its rapid growth of runners that have the ability to root at the node and create new plants. As the kudzu patch grows older it will become harder to control due to increased root and rhizome biomass. Researchers began to evaluate herbicides for kudzu control in the 1950s when the vine was beginning to be viewed as a threat rather than a beneficial plant. Davis and Funderburk (1964) began testing existing herbicides in 1956 on an old field that had been taken over by kudzu. Using a 1:1 mixture of propylene glycol butyl ether esters of 2,4-dichlorophenoxyacetic acid (2,4-D) and 2,4,5-trichlorophenoxyacetic acid (2,4,5-T) in 200 gallons per acre (gpa) of water at rates of 1, 3, and 5

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lbs per acre. Beginning in the mid 1960s, Tordon 10K pellets became the most widely used method of controlling kudzu. Given price increases in Tordon K in the 1980s, the most effective herbicides for treating patches of kudzu were Tordon 10K pellets, Tordon 101 M, and Spike 40P pellets. At the time Spike 40P pellets were still an experimental herbicide and price information was not available, but it was found that applications of Tordon 101 M provided comparable levels of control to Tordon 10K at a much lower cost. However, if controlling kudzu that is draped over trees is necessary, Miller and True (1986) discovered that Garlon 4 was the most effective herbicide. Although herbicide alone has been proven to provide complete control of kudzu, other aspects of integrated pest management such as fire and induced competition control have also been studied.

Through the years Tordon 101 M has proven to be one of the most effective and economical herbicides available for kudzu control (Dickens and Buchanan 1971, Miller 1985, Michael 1986, Miller 1988, Miller 1996). Picloram, the active ingredient in Tordon, has been found to move rapidly through soil and into nearby streams (Michael 1987, Michael and others 1989). Given this, extreme caution should be used when treating kudzu near streams or other bodies of water. Veteran 720 can be used near water as long as it is not directly sprayed on the water. If contact with water is probable Rodeo or Escort may be used; however, repeated applications will be necessary (Everest and others 1991). It is also important to note that for Tordon to be most effective, it needs rainfall 2 to 5 days after it is applied. This will wash the herbicide into the soil where it can be absorbed by the roots (Miller 1996). The suggested application rate for Tordon 101 M is 2 gpa followed by an additional treatment two years later, and spot treatment two years after that (Miller 1996). Dickens and Buchanan (1971) reported that Tordon 101 M was equally effective when applied between May 22 and October 28.

Evaluating forest plantation establishment and management can utilize before-tax financial criteria (Gunter and Haney 1984, Klemperer 1996, Bullard and Straka 1998, Grebner and others 2003). Before-tax analysis may include property taxes and severance taxes as annual and single-sum costs in a discounted cash flow model, but it does not consider a landowner's marginal tax rate or capital gains (Bullard and Straka 1998).

DATA

The kudzu control information applied in this study was obtained from both published and unpublished sources. Research by Ezell and Nelson (2006) is based on an ongoing study where they evaluated the impacts of alternative herbicide treatments on kudzu patches in MS and SC. Plots were sprayed and percent brown up and percent kudzu cover were calculated from ocular estimates four times after initial spray. Table 1 provides herbicide impact on kudzu cover for plots treated in MS.

In this study, for simulating the afforestation of a site with loblolly pine, we used PTAEDA 3.1 to project pine growth to a fixed rotation age. Harvesting activities occurred as either thinning operations or final stand replacement cut. Rotation lengths for afforested sites to pine plantations were normalized to 30 years. Herbicide applications occurred in late summer of the first year. For pine sites, planting occurred the following spring. In addition, on older kudzu sites, re-application of herbicides by backpack sprayers occurred during the second summer.

Cost information used in this study was collected through personal communication with herbicide vendors and from the Forest Landowners Association. In this analysis, a 6 percent real discount rate was used. Average costs per acre for afforestation in MS in 2005 are reported in table 2.

Per acre values of these costs, for herbicide treatments, were calculated using container size, price, and adjustments for application rates. For older kudzu patches, percent kudzu coverage one year after initial treatment (table 1) was used to adjust the re-application cost when using a backpack sprayer to spot control resprouting (table 2).

The price data used to compute harvest values was taken from Timber Mart South. Mississippi Region 1 data was averaged for the four quarters of 2005. Averaging was performed for pine sawtimber and pine pulpwood. In addition, it was assumed that landowners would be able to lease their land for lease hunting purposes at an average of $5.50 per acre per year (table 3).

METHODS

This study compares three alternative management regimes for eradicating kudzu patches and afforestation of appropriate sites to pine plantations in Mississippi. Land Expectation Value (LEV) on a before-tax basis was used to evaluate the feasibility of these practices. Although the examples are hypothetical, scenarios reflect a realistic commercial design. Herbicides were dispersed by pumper truck. Relative age of kudzu was categorized as either old or young with tuber size being positively correlated with time.

RESULTS

To compare the investment returns for controlling kudzu using alternative management regimes, LEV was calculated for each regime given the before-stated assumptions. Figure 1 illustrates the before-tax LEVs for alternative management regimes that control kudzu and afforest the site to a pine plantation.

The results in figure 1 clearly display differences in before-tax LEVs between regimes and kudzu patch age. In general, the results show that the LEV for treating older kudzu patches is lower than treating younger patches. The average LEV for the alternative regimes treating the older kudzu patches is $494.18 per acre with a range of $387.67 to $622.75 per acre. The average LEV for the alternative regimes treating the younger kudzu patches is $588.05 per acre with a range of $532.19 to $680.40 per acre. The results suggest that for controlling older or younger kudzu patches applying 4 ounces of Escort will provide the greatest financial return and biological control. In general, all three treatments will

Table 1–Average percent kudzu cover by treatment and time of observation in Mississippi 2004

	Time of Observation			
Treatment (ounces per acre)	June	July	August	September[b]
Escort (4)	3.3a[a]	8.3a	18.0a	23.3
Transline (21)	28.3b	37.3b	57.0b	76.7b
Tordon K (128)	3.0a	10.0a	16.7a	20.0a

[a] values in a column followed by same letter do not differ α=0.05.

[b] increase in coverage due to vine growth—no new sprouts in any treatment area except with Transline application.

Source: Ezell and Nelson (2006).

Table 2—Average cost per acre by activity for Mississippi in 2005[a]

Activity	$ per acre
Seedlings[b]	$34.12
Hand planting	$37.16
Land use tax[c]	$5.00
Annual management fees	$5.00
Burn	$21.08
Escort XP (4 ounces)	$66.40
Transline (21 ounces)	$54.81
Tordon K (128 ounces)	$172.80
Truck application	$100.00
Backpack spraying	$35.00

[a] Herbicide cost information obtained by personal communication with Kenneth Moss.

[b] Seedling price is $0.05 per seedling and 726 seedlings planted per acre.

[c] Average per acre property tax for forestland in Mississippi is approximately $5.

Table 3—Price and revenue information for standing timber and fee hunting in Mississippi in 2005[a]

Species	Prices
Pine sawtimber	$434.2 per 1000 board-foot Doyle
Pine pulpwood	$8.35 per cord
Hunting leases[b]	$5.50 per acre per year

[a] Timber prices from TimberMart South.
[b] Dr. Stephen Grado, pers.comm. (2005).

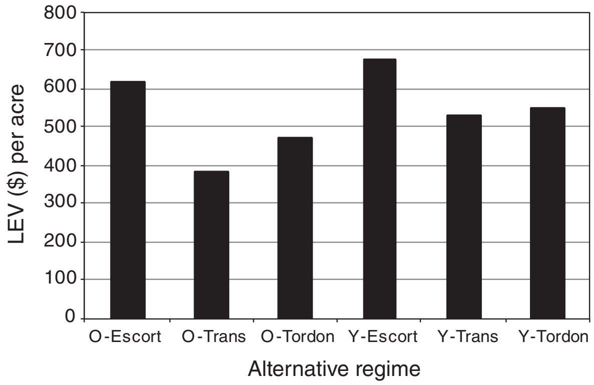

Figure 1—Before-Tax Land Expectation Values for alternative treatments by truck controlling old and young kudzu and establishing pine plantations.

lead to positive financial returns from controlling kudzu and afforesting appropriate sites to pine plantations.

DISCUSSION

An important issue, when evaluating this study's results, is whether herbicides are physically available and the concentration of active ingredient per container. Since Ezell and Nelson (2006), which used 2004 field data, the United States Environmental Protection Agency and Dow Agrosciences LLC reached an agreement to reduce the approved rate of use of Tordon K on a per acre basis. This agreement was due to various environmental concerns that pertained to the active ingredient, picloram, being a very mobile molecule getting into the water table. This has been an issue in agricultural regions outside the Southern United States. The importance of this agreement indicates that the expected results for controlling kudzu patches using Tordon K will not be effective without repeated spraying which will increase costs and reduce investment returns for landowners.

Controlling kudzu with herbicides can be a costly alternative for private landowners. Fortunately, there are multiple federally funded cost-share programs that offer assistance to private landowners enabling them to combat the spread of non-native invasive plant species such as kudzu. One such program is the Environmental Quality Incentives Program (EQIP). EQIP is a well funded cost-share program sponsored by the Natural Resources Conservation Service that provides technical and financial assistance to landowners for conservation management on agricultural and forested lands.

CONCLUSIONS

In summary, the goal of this study was to examine the monetary returns for controlling kudzu using alternative herbicide treatments. The analytical approach utilized before-tax LEV estimates to conduct a comparative analysis of different control and afforestation regimes. The results suggested that the most cost-effective way to control kudzu patches is to spray Escort XP by a ground dispersal unit. This application was appropriate for both young and old kudzu patches.

This research serves as a basis for conducting additional invasive species control work on both pine and hardwood sites. Further economic analysis research is necessary to address the federal and state incentive programs because the potential benefits to the individual landowner and society can be substantial. In addition, future work on invasive species in relation to state income taxes would be useful.

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EFFICACY OF 'HACK AND SQUIRT' APPLICATION OF IMAZAPYR, TRICLOPYR, AND GLYPHOSATE TO CONTROL THE INVASIVE TREE SPECIES CHINESE TALLOWTREE

Charles A. Gresham[1]

Abstract—In May 2005, 12 plots approximately 21 by 27 m each were established on the exterior bank of a dredge spoil area in Georgetown, SC. The tree cover was primarily Chinese tallowtree, but there were also live oak trees in each plot. Also in May 2005, Chinese tallowtrees (d.b.h. > 2.4 cm) in three randomly selected plots received a 'hack and squirt' application of imazapyr (50 percent v/v Habitat), tallowtrees in three plots received triclopyr (50 percent v/v Garlon 4) by 'hack and squirt' injection, and the tallowtrees in three plots received glyphosate (undiluted AquaNeet) by 'hack and squirt' injection. Three plots were an untreated control. The d.b.h. and percent defoliation of all trees (d.b.h. > 2.4 cm) were tallied in July 2005 and May 2006. The imazapyr treatment had the highest percent (96 percent in May 2006) of tallowtrees in the highest defoliation class (75 to 100 percent defoliated). Triclopyr plots had 41.3 percent in the highest class in 2006. Glyphosate plots had 62 percent in the highest class in 2006. The live oak trees (4 to 84 cm d.b.h.) did not show any herbicide damage in any treatment. These results indicate that imazapyr can be used to eradicate Chinese tallowtree by 'hack and squirt' injection without short-term (12 months) damage to dominant live oak trees.

INTRODUCTION

South Carolina's Coastal Plain forests and wetlands are rich with invasive species; some are widespread throughout the state and some are restricted to the coastal counties. Species that occur throughout the state include kudzu (*Pueraria lobata*), privet (*Lugustrium sinense*), tree of heaven (*Ailanthus altissima*), and cogon grass (*Imperata cylindrica*). Chinese tallowtree (*Sapium sebiferium*), beach vitex (*Vitex rotundifolia*), and tamarisk (*Tamarix gallica*) are restricted to coastal habitats in South Carolina. One approach to eradicating these species is either ground or aerial broadcast spraying of one of several modern herbicides. Although this technique is effective over large areas, species selectivity is achieved only by avoiding the non-target species, which negates some of the economy of the broadcast spraying. 'Hack and squirt' injection of herbicides gives users techniques to not only select which species to treat, but also which size class within each species to treat or leave. This highly selective technique allows the user to inject a powerful, non-selective herbicide to kill undesirable species. There are at least two disadvantages to using the hack and squirt technique. First, the method is slow, thus expensive, because it is a labor-intensive, manual operation. Second, soil active herbicides may be released from the target trees to the soil and subsequently be picked up by non-target vegetation. This second concern is especially critical when a crop species is to be planted where the previous vegetative cover was injected with a soil active herbicide or where a crop species is already established among the target species. The purpose of this research was to determine the effectiveness of a hack and squirt injection of three herbicides (glyphosate, imazapyr, and triclopyr) in killing Chinese tallowtrees and to monitor the live oak (*Quercus virginiana*) trees growing among the Chinese tallowtrees for possible herbicide sensitivity.

METHODS

The study area was the outer bank slope of a dredge spoils area on Winyah Bay in Georgetown County, SC (33° 20' 12.63 sec N, 79° 15' 15.04 sec W). The soil was the dredged spoils from Winyah Bay and was fine-textured. On March 29, 2005, 12 plots were established on the exterior slope of the east spoils area dike. The plots were bounded on the west (upper) side by the access road on the crown of the dike, on the east (lower) side by the freshwater marsh that surrounds the spoil area; the north and south sides were set to produce a 27-m wide plot. Plot depth varied with the height of the dike and ranged from 15 to 20 m.

Three 'hack and squirt' treatments were applied to each of three randomly selected plots the morning of May 9, 2005 and the three untreated plots were controls. Chinese tallowtrees (d.b.h. > 2.4 cm) only received a 'hack and squirt' application of imazapyr (50 percent v/v Habitat), triclopyr (50 percent v/v Garlon 4) or glyphosate (undiluted AquaNeet). A hatchet was used to wound the trees at d.b.h. and the appropriate solution was sprayed in the wound from a handheld spray bottle. Trees were wounded at approximately 3-cm intervals along the circumference. The d.b.h. and percent defoliation of all trees (d.b.h. > 2.4 cm) in all plots were tallied on June 6, and July 25, 2005 and again on May 8, 2006. Percent defoliation was visually estimated to four defoliation classes: 0 to 25, 25 to 50, 50 to 75 and 75 to 100 percent. For the May 2006 survey, a 0 percent and a 100 percent defoliation class was added, and the lowest class was changed to 1 to 25 percent and the highest class changed to 75 to 99 percent defoliation. Stem frequencies were tallied by treatment and defoliation class and the Pearson Chi-square statistic was used to compare treatments or groups of treatments.

RESULTS AND DISCUSSION

The study area tree cover consisted of a few large live oak trees and many Chinese tallowtrees (table 1). Loblolly pine, sugarberry and groundsel tree were minor components. Treatment effects were observed one year after treatment (table 2). The Chi-square statistic for all treatments was highly significant (P < 0.01) indicating that one or more of the treatments was different. Chi-square tests of the three

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Table 1—Mean (and standard error of the mean) pretreatment basal area and stem density by species for all 12 plots

Species	Basal Area	Density
	m^2ha^{-1}	*stems ha^{-1}*
Baccharis halimifolia	0.01 (0.027)	4.6 (11.4)
Quercus virginiana	8.74 (4.91)	47.96 (37.81)
Pinus taeda	0.57 (1.32)	17.14 (42.82)
Celtis laevigata	0.10 (0.20)	6.69 (9.90)
Sapium sebiferum	7.31 (4.74)	722.88 (507.12)
Total species	16.74 (3.08)	849.22 (474.07)

Table 2—Defoliation class frequencies of *Sapium sebiferum* 12-months after treatment

	Defoliation Class					
Treatment	0 %	1 to 25 %	26 to 50 %	51 to 75 %	76 to 99 %	100 %
Control	14	147	42	13	8	4
Triclopyr	16	37	20	11	28	31
Glyphosate	1	18	9	16	49	23
Imazapyr	1	2	0	0	11	61

herbicide treatments were highly significant, indicating the three herbicides produced different levels of defoliation. Chi-square tests of the defoliation class distributions of imazapyr and control, glyphosate and control, triclopyr and and glyposate were all significantly different. These tests indicate that each of the herbicide treatments were different from the controls, thus the herbicides were effective. The defoliation class distribution of the imazapyr treatment has all but three trees in the two highest defoliation classes, indicating that this was very effective. The defoliation class distribution of live oak trees only was not significantly different among the four treatments (P = 0.27), which indicates that the herbicides did not significantly affect the live oak trees. From these results we concluded that all three herbicides were effective in killing Chinese tallowtrees when applied with a 'hack and squirt' technique. Among the three herbicides, imazapyr as a 50 percent Habitat solution was the most effective at defoliation. Finally, live oak trees were not affected by the Chinese tallowtree treatments.

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Site Preparation

Moderator:

HANS WILLIAMS

Stephen F. Austin University

USE OF CARFENTRAZONE FOR CONTROL OF NATURAL PINE IN FORESTRY SITE PREPARATION AREAS

Andrew W. Ezell and Jimmie L. Yeiser[1]

Abstract—Carfentrazone was applied in combination with imazapyr alone and three-way mixes with imazapyr and glyphosate to evaluate efficacy of natural pine control during site preparation activities. Results from four sites (two in MS, and one each in TX and SC) indicated that carfentrazone could assist in the control of small pine seedlings (less than six inches tall), but the control provided was not at a level considered acceptable for operational purposes. Larger pine seedlings (greater than one foot tall) were not adequately controlled by any of the treatments and shielding by other vegetation was an important factor in the control of smaller pine seedlings. Carfentrazone is not labeled for use in forestry applications and results from this study did not provide any rationale for pursuit of such labeling.

INTRODUCTION

Site preparation continues to be a major emphasis in stand establishment. The importance of the control of hardwood species has been researched extensively (Lockaby and others 1988, Morris and Lowery 1988, Shiver and Fortson 1979, and Slay and others 1987) but the control of pine seedlings has received less emphasis. Historically, control of natural pine seedlings was not considered a problem. In some situations these seedlings were a welcome addition to the planted seedlings as higher initial seedling densities were more desirable, survival of planted stock was often less than desirable, and genetically improved seedlings were not available for use. In addition, the use of intensive mechanical methods and/or fire often provided extensive control of any naturally occurring pine seedlings. Even as the shift from mechanical to chemical site preparation occurred, the use of fire continued to provide control of natural pine seedlings until recently when fire has become a site preparation tool which is utilized infrequently across the South. Currently, forest land managers are often faced with planting areas which have very little hardwood competition but may have tens of thousands or hundreds of thousands of naturally occurring pine seedlings per acre. These seedlings represent intense competition for the planted genetically improved seedlings which will result in a significant loss of growth and quite often result in the necessity of precommercial thinning. The objectives of this study were to (1) evaluate the use of carfentrazone for control of natural loblolly pine seedlings and (2) evaluate control of hardwood species using tank mixes which include carfentrazone.

METHODS

The study was installed on a total of four sites. Two sites were in MS and included one study area with small (less than six inch height) and one study area with large (greater than one foot height) pine seedlings. One study site was located in both TX and SC, both of which had small pine seedlings. With the exception of one site in MS, all sites had been harvested the year prior to study installation. All were representative of pine regeneration areas in the middle and upper coastal plain in that they were covered with herbaceous and woody vegetation of undesirable species. Study sites were also selected on the presence of natural pine seedlings. Pine seedling density in the study areas ranged from about 800 seedlings per acre (large seedling site in MS) to about 500,000 seedlings per acre.

A total of eight herbicide treatments were applied at each site (table 1). In addition, an untreated check was utilized as a treatment at each site. All treatments were replicated four times at each site in a randomized complete block design. Treatments were applied as an aerial spray simulation using CO_2-powered backpack sprayers with a pole extension and KLC-9 nozzle. Spray volume was 10 gallons per acre (g.p.a.). Each treatment plot was 30 by 100 feet with a sample area of 10 by 80 feet centered in the treatment plot. All treatments were applied during the first two weeks of August, depending on the study site.

Prior to treatment, all hardwood stems in the sample areas were recorded by species and height class. Small pines were recorded as subsamples (three sample points within the sample area) for small pines or as a total count for the area (large seedlings). Percent brownout was evaluated ocularly for all vegetation classes at two weeks after treatment (2WAT) and 4WAT. Control of pine and hardwoods was evaluated by recording living stems in October of the year following treatment (14 months after treatment). Data was analyzed using ANOVA and means were separated with Duncan's New Multiple Range Test.

RESULTS AND DISCUSSION

Brownout

Average percent 4WAT brownout is presented in table 2. Brownout at 2WAT was appreciably less than 4WAT (as expected) and would not represent conditions that would carry a fire. By 4WAT, treated sites would have carried a fire if the treatments contained glyphosate (Treatments 4-7). These were the only treatments that provided acceptable brownout by 4WAT. Imazapyr is known to be slow but thorough and provide slow brownout response. The addition of carfentrazone did not provide enhanced brownout.

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Table 1—List of treatments in carfentrazone field trials

Trt. No.	Herbicide and Rate/A
1	Chopper EC (40 oz) + Carfentrazone (2 oz) + NIS[1] (0.25% v/v)
2	Chopper EC (40 oz) + Carfentrazone (4 oz) + NIS (0.25% v/v)
3	Chopper EC (40 oz) + Carfentrazone (6 oz) + NIS (0.25% v/v)
4	Chopper EC (32 oz) + Carfentrazone (2 oz) + Razor Pro (64 oz)
5	Chopper EC (32 oz) + Carfentrazone (4 oz) + Razor Pro (64 oz)
6	Chopper EC (32 oz) + Carfentrazone (6 oz) + Razor Pro (64 oz)
7	Chopper EC (32 oz) + Razor Pro (64 oz)
8	Chopper EC (40 oz) + MSO[2] (10% v/v)
9	Untreated Check

[1]NIS = nonionic surfactant
[2]MSO = methylated seed oil

Hardwood Control
Hardwood species on the study sites included most of the major species (or species groups) encountered on site preparation areas across the South (table 3). Control of blackgum, sweetgum, white oak, post oak, and red maple was very good for all treatments in most, if not all, replications. Hickory control varied and that is believed to be due to layering of vegetation and resultant shielding of target of stems. It was noted that all surviving hickory stems were in the lower height classes and imazapyr alone (Treatment 8) provided excellent control as compared to Treatments 1-3 wherein taller hickory stems were controlled, but not all shorter stems. Control of the red oak group was variable, and this has been noted before (Harrington and others 2002). Overall, hardwood control in the study could be considered very good to excellent.

Pine Control
Two items were most apparent in the control of pine seedlings in this study. First, small seedlings were much easier to control than larger seedlings (table 4). The only treatments which provided any control of the larger pine seedlings were those which contained glyphosate. Imazapyr is not expected to control loblolly pine, and the addition of carfentrazone (Treatments 1-3) provided no control of the larger seedlings. Second, while the addition of carfentrazone appeared to assist with control of small pines (Treatments 1-3), the level of control provided would not be considered acceptable in operational applications. Only the treatments containing glyphosate (Treatments 4-7) provided levels of control which could be considered acceptable, and in those treatments, the addition of carfentrazone did not significantly improve pine control. Overall, while carfentrazone may provide some assistance in control of natural pines, it is ineffective on larger seedlings and does not provide operationally acceptable levels of control on small pine seedlings.

Table 2—Average percent brownout by vegetation type (average all reps)

Trt. No.	Gross	Forbs	Hardwoods	Pines
	percent			
1	8.9	9.7	5.3	2.7
2	23.4	31.6	5.8	7.6
3	19.4	33.7	6.2	7.1
4	70.3	77.4	22.4	68.3
5	70.1	84.6	27.3	72.1
6	78.3	82.7	29.9	81.1
7	77.3	77.4	28.3	63.4
8	15.8	15.7	7.3	8.7
9	3.4	4.2	1.0	0.0

Table 3—Average percent control of principal hardwood species in carfentrazone field trials (average all reps)

	Species[1]						
Trt. No.	BLG	HIC	SWG	REM	REO	POO	WHO
	percent						
1	98.1a[2]	39.4c	88.3a	82.6b	78.3a	95.8a	100.0a
2	100.0a	29.7c	79.8b	77.3b	74.3a	100.0a	100.0a
3	95.3a	61.3b	85.3a	79.4b	90.1a	100.0a	79.3b
4	94.9a	97.4a	90.9a	73.4b	67.5b	100.0a	100.0a
5	91.3a	100.0a	87.6a	74.2b	50.2c	83.3b	100.0a
6	93.0a	100.0a	73.4b	85.1b	65.9b	100.0a	100.0a
7	100.0a	100.0a	97.6a	100.0a	63.6b	94.4a	100.0a
8	95.8a	100.0a	82.6ab	100.0a	86.1a	100.0a	100.0a
9	17.3b	+33.6[3]d	+18.3c	1.6c	+9.3d	22.5c	21.3c

[1] BLG=blackgum, HIC=hickory, SWG=sweetgum, REM=red maple, REO=red oaks, POO=post oak, WHO=white oak
[2] values in a column followed by the same letter do not differ at α=0.05
[3] plus sign indicates an increase in stems

Table 4—Average percent reduction of pines by treatment in carfentrazone field trials (average all reps)

Trt. No.	Small pines (3 sites)	Large pines (1 site)
	percent	
1	47.4b[1]	0.0c
2	39.8b	0.0c
3	34.4b	0.0c
4	83.3a	50.7b
5	79.9a	50.0b
6	88.8a	81.5a
7	81.4a	75.5a
8	41.3b	0.0c
9	36.5b	0.0c

[1] values in a column followed by the same letter do not differ at α=0.05

SUMMARY

Site preparation will continue to be a concern in pine plantation management in the South. Control of natural pine seedlings will become increasingly important as the intensity of plantation management increases. Current site preparation applications provide variable results of natural pines. Carfentrazone will not be the absolute answer to this problem, is not labeled for forestry applications, and will probably not be labeled for such use.

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STRATEGIES TO ACHIEVE LONG-TERM BENEFITS FROM MULTIPLE OPERATIONAL HERBICIDE APPLICATIONS IN LOWER COASTAL PLAIN PINE STANDS

Harold E. Quicke and Dwight K. Lauer[1]

Abstract—Studies were installed on a range of soils to examine different post-plant herbaceous weed control timings following different site preparation timings with Chopper® herbicide. Chopper site preparation treatments were applied after bedding and included two application dates (August versus November). Pines were planted in winter following site preparation. Site prep was followed with four different post-plant herbaceous weed control timings. This report examines pine growth after five years and relates optimal herbaceous weed control strategies to vegetation cover levels in the absence of weed control. Contrary to expectation, the November Chopper application did not increase residual weed control over the August application. The earlier Chopper application date resulted in better growth than the later date on four of five sites. Optimal strategies for post-plant herbaceous weed control were highly dependent on site, ranging from two consecutive years of weed control on a silt-loam soil to no benefit from any additional weed control on spodosols.

INTRODUCTION

Conventional wisdom indicates that site preparation with Chopper herbicide should occur late in the year for best control of woody vegetation and best residual weed control into the first pine growing season; that post-plant herbaceous weed control treatments should occur early in the first pine year; and that there is little benefit from a second year of herbaceous weed control. These ideas are derived mainly from studies that looked at site preparation or herbaceous weed control as independent treatments and where the quality of modern operational herbicide prescriptions was not considered. Questions which have been poorly addressed include: (1) Does late season site preparation with Chopper result in better residual control in the year following treatment than earlier season treatment? (2) Does late-season site prep result in the best pine growth? (3) Is herbaceous weed control early in the first year always best? (4) Are there any situations where two consecutive years of herbaceous weed control are desirable? To answer these questions a series of studies were installed on Lower Coastal Plain, Upper Coastal Plain and Piedmont sites. These studies used modern operational prescriptions to look at integrated systems of site prep and herbaceous weed control. This paper describes fifth-year results for five Lower Coastal Plain installations.

METHODS

Treatments included 48 ounces Chopper herbicide applied after bedding at two different timings (August versus November). Pines were planted in winter following site preparation. Post-plant treatments were herbaceous weed control (HWC) applied at different times as follows: (1) never, (2) March of the first pine year, (3) June of the first pine year, (4) March of the second pine year, (5) June of the first pine year followed by March of the second pine year. Treatments were arranged in a split-plot design with site prep timing as the main-plot factor and HWC timing as the subplot factor. Each installation included three replications. Recolonization of vegetation was evaluated in June, August, and October of the first pine growing season and June and October of the second pine growing season. Pines were measured at the end of the first three growing seasons and at the end of the fifth growing season. Chopper site prep treatments included Garlon™ 4 at either 1 or 2 pints for control of blackberry. Herbaceous weed control treatments were 4 ounces Arsenal® Applicators Concentrate plus 2 ounces Oust®.

RESULTS AND DISCUSSION

Analysis of variance indicated no interaction between site prep timing and HWC timing. Consequently, the discussion focuses on main effects.

Residual Control

Contrary to expectation, the November Chopper site prep timing did not improve residual control in the year following treatment over the August timing. Possible reasons are: (1) direct control of some perennial herbaceous species is improved when applications are made at a time when they are actively growing instead of later in the year when they have senesced, and (2) earlier season treatment may reduce the seed source for some species. In this study, species that were controlled better with earlier season site prep included bluestem grasses, swamp sunflower, pokeweed and sumac.

Site Prep Timing Effect on Pine Growth

August Chopper site prep treatment resulted in better growth than November treatment on four of the five sites. The earlier site prep date resulted in a 2 to 15 percent increase in mean pine stem volume over the later timing. This confirms results from a previous study installed on four Lower Coastal Plain sites that examined a larger range of site prep timings and documented larger growth gains from earlier season Chopper site prep treatments (Lauer and Quicke 2006).

Herbaceous Weed Control Timing Effect on Pine Growth

Optimal timing for herbaceous weed control was highly dependent on site. Sites are described below in terms of soil types. The CRIFF soil types are from Jokela and Long (2000).

1. The Oakdale, LA site had a medium-well to poorly-drained silt-loam soil (Glenmora/Caddo-Messer series). On this site herbaceous weed colonization was prolific

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in the absence of post-plant HWC. Herbaceous cover in the first pine year increased from 27 in June to 93 percent by October. Under these conditions (high herbaceous colonization) the best timing for a single HWC treatment was March of the first year. This timing increased pine growth by 29 percent compared to no HWC. The best response was from two consecutive years of HWC which resulted in a pine growth response of 44 percent compared to no HWC.

2. The Kings Ferry, FL site had a CRIFF A group soil (poorly drained clay) and the Green Swamp, NC site had a very-poorly to poorly-drained sandy-loam soil (Nakina/Grifton series). On these sites, herbaceous cover in the absence of post-plant HWC increased to 46 and 36 percent, respectively, by October of the first pine year. Under these conditions (moderate herbaceous colonization) the best HWC timing was March of the second pine growing season. This timing increased pine growth by 25 and 12 percent, respectively, compared to no HWC.
3. The Mount Pleasant, GA site had a CRIFF C group soil with a sandy surface, a spodic layer at 12 to 36 inches and argillic layer at 30 to 48 inches. The Tennille, FL site had a CRIFF D group soil (spodic layer with no argillic layer). On these two sites herbaceous cover in the absence of post-plant HWC never exceeded 20 percent in the first pine year. Under these conditions (low herbaceous colonization) there was no benefit from any of the HWC timings.

CONCLUSION

While more studies installed over multiple years would provide a better inference base, results from this study indicate that immediate productivity benefits are possible with site-specific timing of Chopper site preparation and Arsenal + Oust herbaceous weed control. This study demonstrates that optimal HWC timings are dependent on expected first year weed cover in the absence of HWC:

1. If expected maximum first year weed cover is 90 percent, the optimal strategy is two consecutive years of HWC or, if only one HWC treatment is to be used, the optimal timing is early in the first pine growing season.
2. If expected maximum first year weed cover is 30-50 percent, the optimal HWC timing is early in the second pine growing season.
3. If maximum first year cover never exceeds 20 percent, there is no need for HWC.

To apply these optimal timings in an operational setting, it is necessary to predict weed development in advance. Substituting soil type for expected weed development, these studies suggest the following optimal post-plant HWC timings for Lower Coastal Plain sites where site preparation consists of bedding followed by a Chopper herbicide treatment:

1. On medium-well to poorly-drained silt-loam soils use two consecutive years of HWC.
2. On CRIFF A group soils and very-poorly to poorly-drained silt-loam soils apply HWC early in the second year.
3. On CRIFF C and D group soils (Spodosols) no HWC is required.

Rainfall patterns and the presence of specific weed species may change outcomes. These guidelines provide a framework which can be built upon using operational experience.

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SPLIT-SEASON HERBACEOUS WEED CONTROL FOR FULL-SEASON SEEDLING PERFORMANCE

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Abstract—Results from four loblolly pine (*Pinus taeda* L.) sites, one in each of MS and TX in 2001 and again in 2002, are presented. Twelve herbicide treatments and an untreated check were tested. Herbicide treatments were applied early (mid-March), late (mid-May), both timings, or not at all to achieve, early- late-, full-season, or no weed control. When averaged across all four sites and compared to the early treatment, bare ground was less from April through July and April through November on late treated and untreated plots, respectively. Full-season weed control provided numerically more bare ground than other treatments. When averaged across sites and compared to the early treatment, survival, total heights at ages one and two, and ground line diameters at age one were less on other treatments. Results are biologically important to managers. Many of the herbicide treatments tested can be applied early or late for the same cost but achieve excellent herbaceous weed control at different portions of the growing season. Early weed control consistently provided numerically more seedling performance than other treatments.

INTRODUCTION

Herbicidal site preparation and herbaceous weed control (HWC) were heavily researched during the 1980s. Then, one preparation method commonly preceded planting. Today, not just one but often two, three or more methods precede planting. Furthermore, regeneration lag is briefer now with sites prepared and replanted as quickly following harvest as possible.

Forest managers in the Southeastern United States are concerned about the negative impact of herbs on loblolly pine seedling performance. Herbaceous weeds are known to compete with newly planted seedlings for water, nutrients, light, and space (Nelson and others 1981, Tiarks and Haywood 1986, Zutter and others 1986). When compared to plantings without HWC, treated loblolly pine plantations are commonly characterized by increased planting survival that persists into mid-rotation (Clason 1987), enhanced growth (Creighton and others 1987, Glover and others 1989, Holt and others 1975), early commercial thinning (Glover and others 1989), and shorter rotations (Clason 1989 and Glover and others 1989). Therefore, HWC is a commonly accepted practice in loblolly pine plantation management.

Managers want to know when it is most critical for newly planted seedlings to be weed free. Discussions commonly revolve around several thoughts. The first thought pertains to soil moisture. In general, early in the growing season soil moisture is high and available. Newly planted pines and emerging weeds lack good root-soil contact. Both actively compete for resources while becoming established. Late in the growing season, pines and competitors have established root systems. Weeds consume and reduce resources otherwise available for seedlings at a time when resources are limited. When considering extremes in poorly and excessively drained sites, the above general relationships may not apply. That is, pine seedlings on poorly drained sites may benefit early from the moisture drain of weeds and therefore, need a late release from competitors. Similarly, pine seedlings on excessively well drained sites may be at high risk throughout the season to light competitor levels commonly of no concern on mesic sites. A second thought pertains to the timing of applications and seedling flushes. In spring, weeds emerge and seedlings flush about the same time. New flushes are more vulnerable to over-the-top herbicide treatments than hardened flushes. Thus, pre-emergence applications may offer more safety than post-emergence. Third, managers question the logic of controlling weeds early in the growing season to enhance survival and growth only to later in the same season allow unwanted competition to recolonize the planting site and reduce seedling growth.

The objective of this study was to apply herbicides over the top of newly-planted, loblolly pine seedlings for early-, late-, full-season, or no herbaceous weed control and quantify the resultant seedling survival and growth.

METHODS

A total of five sites were tested. Results from four sites will be presented. One site in TX and one in MS were tested during each of 2001 and 2002. Site characteristics and histories are summarized for comparison in tables 1 and 2.

Twelve herbicide treatments and an untreated check were tested at all sites (table 3). Oust XP, Oustar, Escort XP and Arsenal AC are standards for HWC. Eagre contains 5.4 pounds of glyphosate per gallon of product and lacks surfactant. Herbicides were applied early (mid-March), late (mid-May), both timings, or not at all to achieve early-, late-, full-season, or no weed control. Herbicides were applied at a total volume of 10 gallons per acre and in a 5-foot band centered over the top of seedlings. Treatment plots contained 16 seedlings each. Seedlings were planted on 8 by 10 foot spacing. For each test site, treatments were assigned to four randomized complete blocks. Data were analyzed with SAS using PROC GLM and Duncan's New Multiple Range Test ($P \leq 0.05$ level, SAS 1999).

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Table 1—A summary of characteristics and history for the Texas sites

	Huntington, TX		Woden, TX	
Initiate	2001		2002	
Harvest	May-00		Wildfire summer 01	
Soil	Fine sandy silt loam, pH=5.2		Sandy loam, pH=5.0	
SP1	1-Sep-00 Arsenal AC+Garlon 4, 14oz+2q		None	
SP2	Oct-00, Burned		None	
SP3	Nov-00, Combination plowed		None	
Planted	Hand, 5-Feb-01		Machine, Feb-02	
Applied	9-Mar/11-May		19-Mar/20-May	
Cover	Pre<1%/Post>90%		Pre<1%/Post>50%	
Weed	Grass		Grass	
	Andropogon spp[a]	Panicgrasses	*Andropogon* spp	Panicgrasses
	Rye grass			
	Broadleaf		Broadleaf	
	Carolina nettle	Dogfennel	Horseweed	Poorjoe
	Purple cudweed	Late boneset	Purple cudweed	Venus lookingglass
	Venus lookingglass	Wild geranium	Wild geranium	
	Wooly croton			
	Semi-woody		Semi-woody	
	A. beautyberry	*Hypericum* spp	A. beautyberry	*Hypericum* spp
			Rubus spp	

[a]Names according to Miller and Miller (1999).

Table 2—A summary of site characteristics and history for the Mississippi sites

	Una, MS		Longview, MS	
Initiate	2001		2002	
Harvest	May 2000			
Soil	Silt Loam, pH=5.0		Falkner Silt Loam, pH=5.2	
SP1	Shear & windrowed Sep 2000		Sheared	
SP2	None		Combination plowed	
SP3	None		None	
Planted	Hand, Jan 2001		Hand, Jan 2002	
Applied	6-Mar/1-Jun		11-Mar/20-May	
Cover	Pre<1%/Post>80%		Pre<1%/Post>60%	
Weed	<u>Grass</u>		<u>Grass</u>	
	Andropoogon spp[a]	Panicgrasses	*Andropogon* spp	Panicgrasses
	Roundhead sedge		Dallisgrass	
	<u>Broadleaf</u>		<u>Broadleaf</u>	
	Blue vervain	Common ragweed	Common ragweed	Coneflower
	Desmodium spp	Goldenrod	*Desmodium* spp	Daisy fleabane
	Horseweed	Late boneset	Goldenrod	Horseweed
	Wild garlic	Wooly croton	Ironweed (Vernonia)	Late boneset
			Pokeberry	Rustweed
			Wooly croton	
	<u>Vine</u>		<u>Vine</u>	
	Japanese honeysuckle	Trumpetcreeper	Japanese honeysuckle	Poison-ivy
	Smilax spp	*Vitis* spp		
	<u>Semi-woody</u>		<u>Semi-woody</u>	
	Baccharis spp	*Rubus* spp	A. beautyberry	*Baccharis* spp
	Hypericum spp		*Rubus* spp	

[a]Names according to Miller and Miller (1999).

Table 3—Twelve herbicide treatments and an untreated check were tested at all sites. Treatments were applied early (mid-March), late (mid-May), both timings, or not at all to achieve early-, late-, full-season or no weed-free growing conditions for seedlings.

Weed-Free	Mid-March	Mid-May
Early	Oust XP 3oz	Untreated
Early	Oustar 13oz	Untreated
Early	Oustar 19oz	Untreated
Early	Arsenal AC+Oust XP 4+2oz	Untreated
Late	Untreated	Oust XP+Escort XP+Eagre 2+0.5+12oz
Late	Untreated (2002 only)	Arsenal AC+O XP 4+2oz (2002 only)
Full	Oustar 13oz	Escort XP 0.5oz
Full	Oustar 13oz	Oust XP 2.0oz
Full	Oustar 13oz	Eagre 12oz
Full	Oustar 13oz	Oust XP+Escort XP+Eagre 2+0.5+12oz
Full	Arsenal AC+Oust XP 4+2oz	Oust XP+Escort XP+Eagre 2+0.5+12oz
Full	Velpar L 32oz	Oust XP+Escort XP+Eagre 2+0.5+12oz
None	Untreated	Untreated

RESULTS AND DISCUSSION

Rainfall

Rainfall was very different in TX during 2001 and 2002. While total rainfall at Huntington was normal, the monthly distribution was badly skewed. For example, droughty months were April, May, July, August and September all of which were > 2 inches below the 29 year monthly mean. To counter this deficit, in June, Tropical Storm Allison provided 9.7 inches in 3 days, the only precipitation for the month. Likewise, December received over 7 inches. This brings the 2001 total for March through December to 38.1 inches while the 29 year total was 37.7 inches. In contrast, Woden rainfall from March through December 2002 deviated little from the 29 year monthly means. Therefore, 2001 and 2002 TX rainfall represents drought and average years and gives insight into extremes in seedling performance.

Weed Control

Numerical and statistical values for weed-free growing conditions (e.g., bare ground) are presented in table 4 and statistical differences expressed in days and months in table 5. Huntington, TX seedlings treated early were more weed-free May to June than those treated late. Woden, TX seedlings treated early were more weed free in April to May, in Una, MS it was June to July and in Longview, MS it was May only (tables 4 and 5). More bare ground was available for late than early treated seedlings during August to November at Huntington and October at Woden (tables 4 and 5). Full-season weed control provided more weed-free space than seedlings treated early during August to November in Huntington, October at Woden, September to November in Una and none in Longview. Untreated seedlings consistently had more competition than treated seedlings (tables 4 and 5).

Early and late timings in TX and Longview, MS provided more than 80 percent July bare ground. Weeds re-colonized plots slowly during hot summer months (table 4). It is no surprise, that bare ground levels on plots receiving full-season weed control were little better than that achieved with either an early or late treatment alone. At Una, MS bare ground for the late timing did not peak until August with weeds re-colonizing more rapidly than on plots treated for early or full-season weeds. At all sites, a portion of the successful re-colonization is attributed to *Hypericum* spp and A. beautyberry, semi-woody species whose tolerance to test herbicides is higher than pine seedlings.

When averaged across all four sites and expressed as a percent of early weed control, bare ground was similar in April for all treatments (table 6). In May and June, bare ground was similar for the late treatment and untreated plots and similar for early- and full-season treatments with the latter significantly better than the former. Bare ground was less for untreated than treated seedlings during months of July through November. October differences were probably of little biological significance since the growing season was largely over and differences reflect the invasion of winter

Table 4—Test plots were evaluated 30-210 (Apr-Nov) days after treatment (DAT) for bare ground (%). Herbicides were applied early (mid-March), late (mid-May), both timings, or not at all to achieve early-, late-, full-season or no weed control for loblolly pine seedlings.

Weed-Free	May	Jun	Jul	Aug	Sep	Oct	Nov	Apr	May	Jun	Jul	Aug	Sep	Oct
DAT	60 [a]	90	120	150	180	210	240	30	60	90	120	150	180	210
	HUNTINGTON, TX 2001							WODEN, TX 2002						
Early	90a	92a	85a	79b	74b	72b	72b	99a	98a	91a	91a	91a	91a	84b
Late	13b	26b	89a	92a	92a	90a	90a	84b	71b	85a	85a	94a	94a	94a
Full	90a	90a	96a	94a	93a	93a	93a	99a	99a	98a	98a	97a	97a	97a
None	12b	17b	28b	28c	22c	21c	21c	85b	63b	46b	46b	37b	31b	13c
	UNA, MS 2001							LONGVIEW, MS 2002						
Early	-	92a	98a	94a	78b	52b	45b	96a	95a	90a	83a	92a	87a	80a
Late	-	53b	25b	89a	62b	56b	35c	95a	63b	87a	86a	86a	88a	81a
Full	-	89a	92a	97a	91a	79a	65a	96a	87a	95a	84a	94a	92a	86a
None	-	60b [a]	19c	3c	0c	0c	0d	76b	48c	23b	1b	3b	0b	0b

[a] Means within a column sharing the same letter are not significantly different (Duncan's New Multiple Range test P≤0.05).

Table 5—Days (d) and months (m) of significantly reduced weed cover for sites and years. Herbicides were applied early (mid-March), late (mid-May), both timings, or not at all to achieve early-, late-, full-season or no weed control for loblolly pine seedlings.

Weed-Free	Early d m	Late d m	Full d m	None d m	Early d m	Late d m	Full d m	None d m
	HUNTINGTON, TX 2001				WODEN, TX 2002			
Early	-	60 May-Jun	0 0	210 May-Nov	-	60 Apr-May	0 0	210 Apr-Oct
Late	120 Aug-Nov	-	0 0	150 Jul-Nov	30 Oct	-	0 0	150 Jun-Oct
Full	120 Aug-Nov	60 May-Jun	-	210 May-Nov	30 Oct	60 Apr-May	-	210 Apr-Oct
None	0 0	0 0	0 0	-	0 0	0 0	0 0	-
	UNA, MS				LONGVIEW, MS			
Early	-	60,30 Jun-Jul, Nov	0 0	180 Jun-Nov	-	30 May	0 0	210 Apr-Oct
Late	0 0	-	0 0	150 Jul- Nov	0 0	-	0 0	210 Apr-Oct
Full	90 Sep-Nov	60, 90 Jun-Jul, Sep-Nov	-	180 Jun-Nov	0 0	30 May	-	210 Apr-Oct
None	0 0	0 0	0 0	-	0 0	0 0	0 0	-

annuals into plots. Because the same products and rates may be used in early and late timings, the cost is the same, yet control is significantly different in May and June. Negative values illustrate the months of major differences in HWC and emphasize the biological importance of careful treatment planning.

Pine Performance

In Huntington, TX, early- and full-season weed control provided similar age one seedling survival at 81 and 77 percent, respectively. The late treatment achieved 61 percent survival, less than both early and full, but greater than checks at 46 percent. This site was sprayed, burned and plowed. Even high intensity site preparation was not a guarantee against planting failure during a severe spring drought. At 545 planted seedlings per acre, the early-, late-, full-season and checks started the rotation with 442, 333, 420, and 251 seedlings per acre. By many standards, only the untreated checks would require a replant. This illustrates the importance of HWC at establishing a well stocked stand. Some non-industrial landowners and state agencies assisting non-industrial landowners do not practice herbaceous weed control in favor of reduced costs. This practice is not biologically based and warrants careful consideration. Survival at Huntington is dramatically lower than other sites illustrating the impact of local conditions on survival and reminding managers to understand the conditions causing performance departures at a specific site from the overall mean. Although little can be done about the weather, when possible, managers should focus on the causal agents reducing local survival to raise programmatic mean performance. In Woden, TX, age one and two survival exceeded 95 percent for all treatments. In Una, MS, age two survival ranged from a low of 82 for checks to 88 percent for all herbicide treatments. At these sites HWC and rainfall were good and resultant seedling survival was good. No statistical differences were detected at these two sites. Survival at Longview, MS is not available.

Growth extremes are represented by TX sites. Greatest treatment differences in growth were recorded at Huntington, TX (table 7). Total heights and ground line diameters after one year were similar for checks and late treated seedlings. fter two growing seasons, total heights and ground line diameters were greater on late than untreated check plots (table 8). At Woden, TX and both MS sites, greatest differences were between treated and untreated seedlings.

When averaged across all four sites, age one survival was statistically similar for all treatments but numerically lower for non-early treatments (table 8). Age one heights were statistically similar for seedlings receiving early- and full-season weed control, late- and full-season weed control and late and no weed control. Seedlings receiving early- and full-season HWC were taller than untreated checks. After two growing seasons, most statistical differences existed between treated and untreated seedlings. When seedling growth was expressed as a percent of the early treatment and averaged, negative values for periods of weed control, although not always statistically different, show lost growth. This is important to managers. The same products and rates, and thus the same cost, may be used for early- and late-timings with lost growth from late times. Full-season weed control comes with a higher cost and less growth than an early treatment.

In conclusion, age-two seedling performances across all four test sites revealed little statistical difference in growth between early-, late-, and full-season weed control. However, late- and full-season weed control provided seedlings that were numerically smaller than those released from weeds early in the season. This pattern was observed at all four individual sites as well. This suggests that early HWC does consistently provide some numerical growth advantage over late- or full-season weed control. Seedlings released with late HWC performed better than those receiving no weed control. The Huntington site demonstrated that HWC, even on intensively prepared sites, during drought years can be the difference in planting success and failure. Data support the practice of not investing in a second herbaceous weed

Table 6—Herbicides were applied early (mid-March), late (mid-May), both timings, or not at all to achieve early-, late-, full-season or no weed control for loblolly pine seedlings. Bare ground is averaged across all four sites and expressed as a percent of Early.

DAT	Apr 30	May 60	Jun 90	Jul 120	Aug 150	Sep 180	Oct 210	Nov 240
Weed-Free								
Early	0.0a	0.0a	0.0a	0.0a	0.0a	0.0a	0.0b	0.0a
Late	-8.1a	-48.9b	-31.0b	-18.2a	2.0a	2.1a	11.5ab	1.4a
Full	0.0a	-2.5a	2.0a	3.9a	7.7a	13.7a	26.0a	36.8a
None	-17.7a	-57.3b	-60.1b	-74.0b	-79.4b	-84.1b	-88.9c	-85.4b

Table 7—Herbicides were applied early (mid-March), late (mid-May), both timings, or not at all to achieve early-, late-, full-season or no weed control for loblolly pine seedlings. Mean seedling performance (total height (H), ground line diameter (GLD) was recorded in November 2001 (age 1) and 2002 (age 2).

Weed-Free	Nov H1 Ft	Nov GLD1 In	Nov H2 Ft	Nov GLD2 In		Nov H1 Ft	Nov GLD1 In	Nov H2 Ft	Nov GLD2 In
HUNTINGTON, TX					WODEN, TX				
Early	1.65a[a]	0.54a	4.40a	1.05a	Early	2.0a	0.48a	5.8a	1.63a
Late	1.26b	0.43b	3.35b	.78b	Late	1.9a	0.44ab	5.7ab	1.60a
Full	1.49a	0.53a	4.17a	1.05a	Full	2.0a	0.51a	5.9a	1.70a
None	1.13b	0.27c	2.54c	.43c	None	1.8a	0.38b	5.1b	1.38b
UNA, MS					LONGVIEW, MS				
Early	1.3a	0.35a	3.5a	0.89a	Early	1.2a	0.31a		
Late	1.3a	0.32a	3.3a	0.85a	Late	1.2a	0.31a		
Full	1.2a	0.37a	3.4a	0.90a	Full	1.1a	0.29a		
None	1.2b	0.26b	3.0b	0.64b	None	1.1a	0.24b		

[a]Means within a column sharing the same letter are not significantly different (Duncan's New Multiple Range test, $p<0.05$).

Table 8—Herbicides were applied early (Mid-March), late (mid-May), both timings, or not at all to achieve early-, late-, full-season or no weed control. Actual mean seedling performances after one (2001) and two (2002) growing seasons are presented for survival, height, and ground line diameter (S, H, GLD) and followed with values expressed as a percent of Early.

Weed-Free	Nov 2001 S1 (%)	Nov 2001 H1 (Ft)	Nov 2001 GLD1 (In)	Nov 2002 H2 (Ft)	Nov 2002 GLD2 (In)
			Actual Means		
Early	88.0a[a,b]	1.55a	0.42a	4.57a	1.19a
Late	81.3a	1.40bc	0.38a	4.11ab	1.08a
Full	86.7a	1.48ab	0.43a	4.49a	1.22a
None	74.7a	1.28c	0.29b	3.56b	0.81b
			Percent of Early		
Early	0.0a	0.0a	0.0a	0.0a	0.0a
Late	-8.2a	-9.9bc	-6.8a	-8.5a	-9.2a
Full	-1.6a	-5.4ab	-0.2a	-1.2a	1.4a
None	-16.3a	-17.9c	-23.6b	-18.1a	-24.8b

[a]Means within a column sharing the same letter are not significantly different (Duncan's New Multiple Range test, $p<0.05$).
[b]Survival means were numerically the same after one and two growing seasons.

treatment on moderately well-drained sites to achieve additional bare ground over that already achieved with one treatment.

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LOBLOLLY PINE GROWTH FOLLOWING OPERATIONAL VEGETATION MANAGEMENT TREATMENTS COMPARES FAVORABLY TO THAT ACHIEVED IN COMPLETE VEGETATION CONTROL RESEARCH TRIALS

Dwight K. Lauer and Harold E. Quicke[1]

Abstract—Different combinations of chemical site prep and post-plant herbaceous weed control installed at three Upper Coastal Plain locations were compared in terms of year 3 loblolly (*Pinus taeda* L.) pine response to determine the better vegetation management regimes. Site prep treatments were different herbicide rates applied in either July or October. Site prep treatments were followed by different herbaceous weed control application timings. July site prep applications performed better than October applications and the higher site prep herbicide rates performed better than the lowest rate. First year herbaceous weed control was more important than second year but first plus second year had the greatest response. Year 3 pine response to the operational vegetation management regime of July chemical site prep with first year herbaceous weed control was comparable to or exceeded year 3 pine response to complete weed control reported in a previous research experiment conducted on similar sites.

INTRODUCTION

Selection of an optimal vegetation control regime to provide the best pine response is complicated because pine response depends on amount and composition of competing vegetation, the degree and duration of vegetation control achieved, and pine tolerance to the herbicides used. It is necessary to examine treatment combinations on many sites and to evaluate pine response, not just weed control. Long-term studies are cost prohibitive because of the large number of potential treatments and because operational treatments change relatively quickly due to new technology and changing treatment costs. However, comparing short-term response to responses observed in older, long-term research trials provides a useful comparison of early stand development and longer-term growth and yield expectations. This paper compares different combinations of chemical site prep and post-plant herbaceous weed control (HWC) to determine the most effective operational vegetation management regimes for establishing Upper Coastal Plain loblolly pine plantations. These operational treatments are compared to more intensive control treatments in a long-term research trial reported by Miller and others (2003).

Miller and others (2003) summarized pine response in a multiple location study designed to determine maximum potential growth of loblolly pine following complete early control of woody, herbaceous, and woody plus herbaceous plants. They found that for high hardwood (> 10 percent stand basal area in hardwood at age 15) or high shrub sites it was more important to control woody competition than herbaceous competition and that the greatest response was achieved by controlling both. Further, that early response to herbaceous weed control was sustained only in the absence of woody competitors. Controlling both woody and herbaceous vegetation increased year 15 merchantable volume 66 percent on average with gains ranging from 23 to 121 percent depending on location.

By comparison, the operational vegetation management strategy examined in this multiple location study used Chopper® (BASF Corporation, Research Triangle Park, NC) herbicide site preparation to control woody vegetation. Different timings of Arsenal® (BASF) Applicators Concentrate plus Oust® (E.I. DuPont de Nemours and Company, Wilmington, DE) herbaceous weed control were applied following Chopper® herbicide site prep to determine the most effective operational treatment regime for both woody and herbaceous control in Upper Coastal Plain loblolly pine plantations.

METHODS

An operational vegetation control study was installed in 2002 to examine timing and rate of Chopper® herbicide site prep followed by post-plant HWC on Upper (Middle and Hilly) Coastal Plain sites. There were six Chopper® herbicide site prep treatments applied as main plot treatments and replicated three times at each of three locations. The six chemical site prep treatments were 32, 48, or 64 ounces per acre Chopper® herbicide applied either in July or October. A tank mix herbicide was included at a constant rate at each location to control blackberry (*Rubus* spp.). Treatments were broadcast using a CO_2 powered backpack research sprayer with a 3 nozzle boom using Turbo Flood® (Spraying Systems, Co., Wheaton, IL) 2.0 nozzles at 10 gallons per acre with the swath centered on tree rows. This technique provided very uniform rates for each subplot row that received subsequent HWC treatments. Six different herbaceous weed control treatment regimes were applied as subplot treatments to tree rows 120 feet (70 feet at the Zwolle location) in length within each chemical site prep treatment plot. Therefore, each herbaceous weed control treatment described in table 1 was applied to 18 subplots at each location. The exception to this was at Barnett Crossroads where an additional main plot treatment without Chopper® herbicide site prep was included. The HWC treatment for all application dates was 4 fluid ounces per acre Arsenal® Applicators Concentrate (AC) plus 2 ounces per acre Oust®. HWC treatments were applied as 6-foot bands using a 2 nozzle (Turbo Flood® 2.0) boom at 15 gallons per acre. Table 2 lists mechanical site preparation, fertilization, Chopper® herbicide application dates and tank mix herbicide for the three study locations.

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Table 1—Description of post-plant herbaceous weed control treatment regimes

Herbaceous weed control timings	Descriptor used in tables and figures
None	No HWC
March 2003	Yr 1 March
March 2003 combined with March 2004	Yr 1 March + Yr 2 March
June 2003	Yr 1 June
June 2003 combined with March 2004	Yr 1 June + Yr 2 March
March 2004	Yr 2 March

Pine groundline diameter (g.l.d.) and total height was measured in December 2005 at the end of the third pine growing season. Year three stem volume index was computed as a volume of a cone using g.l.d. and total height. Vegetation development was measured using ocular estimation of cover through the first two growing seasons.

RESULTS AND DISCUSSION

This experiment used currently available products at operational rates to develop treatment regimes that optimize pine response. There were a total of 36 different Chopper® site prep and herbaceous weed control combinations. There was no interaction between site prep treatment and HWC treatment and results for main effects are provided.

Herbaceous Weed Control Timing

Single applications—Year 3 gains in volume index from the best first year herbaceous weed control treatment were 92, 77, and 159 percent at Barnett Crossroads, Crossett, and Zwolle, respectively (fig. 1). First year HWC was more important than second year HWC at all locations. First year March HWC performed better than first year June at Barnett Crossroads and Zwolle, but not at Crossett where the June application was best. Examination of weed control efficacy and pine response indicated that uncontrolled herbaceous development between March and June at Barnett Crossroads restricted pine growth, that March applications at Zwolle provided better herbaceous control than June applications, and that later season weed control was more important at Crossett due to slow early season development of both pines and herbaceous cover on this soil type.

Double applications—Pines responded positively to an additional year of HWC (fig. 2). Second year March HWC following first year March HWC increased stem volume by 5, 23, and 21 percent at Barnett Crossroads, Crossett, and Zwolle, respectively. At Barnett Crossroads the dominant herbaceous competitor was broomsedge (*Andropogon* spp.). The second year March HWC treatments did not control this dominant competitor resulting in the small response at this location.

The positive pine response to an additional year of weed control is an important finding for landowners. It is reasonable to expect a 20 to 25 percent increase from the additional year of weed control when the treatment is effective. Previous work by Lauer and others (1993) investigated the benefit of a second year of herbaceous weed control on eight sites. Pines on only three of eight sites had a significant diameter response to a second year of weed control. However, Lauer's studies used multiple applications to achieve near complete control of weeds during the first and second years and do not address the question of response from single HWC treatments with modern herbicides in consecutive years.

Table 2—Description of site preparation and fertilization for Chopper herbicide site prep study locations

	Barnett Crossroads, AL	Zwolle, LA	Crossett, AR
Mechanical site prep	April burn and early June single pass rip and bed	June pile and burn with little soil disturbance	Early June bed
Fertilization	None	91 pounds per acre DAP applied in 4 foot band	None
Chopper® herbicide application dates	7/26/2002, 10/11/2002	7/20/2002, 10/14/2002	7/19/2002, 10/15/2002
Chopper® tank mix herbicide	32 ounces per acre Garlon® (Dow Agrosciences, Indianapolis, IN) 4	64 ounces per acre glyphosate (41% formulation)	64 ounces per acre glyphosate (41% formulation)

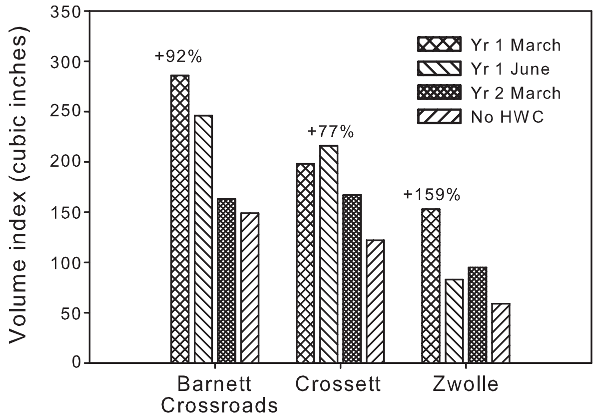

Figure 1—Third year loblolly pine stem volume index for no herbaceous weed control (No HWC) and different timings of a single Arsenal® AC plus Oust® herbaceous weed control treatment. Application timings were first year March (Yr 1 March), first year June (Yr 1 June), and second year March (Yr 2 March). Percentages show the percent gain over No HWC from the best timing at each location.

Chemical Site Prep

Chopper® herbicide timing—July applications yielded greater pine growth than October applications. These differences were most important for the best growing treatments that combined July application with first year HWC. Under these circumstances, the July timing increased growth over October by 12 to 26 percent (fig. 3). These results are consistent with Lower Coastal Plain studies in which Chopper® herbicide site prep earlier in the year resulted in better pine growth (Lauer and Quicke 2006).

Chopper® herbicide rate—Rates of 48 or 64 fluid ounces per acre resulted in better growth than 32 ounces per acre on all three sites. Growth increases from the higher rates ranged from 5 to 20 percent (fig. 4).

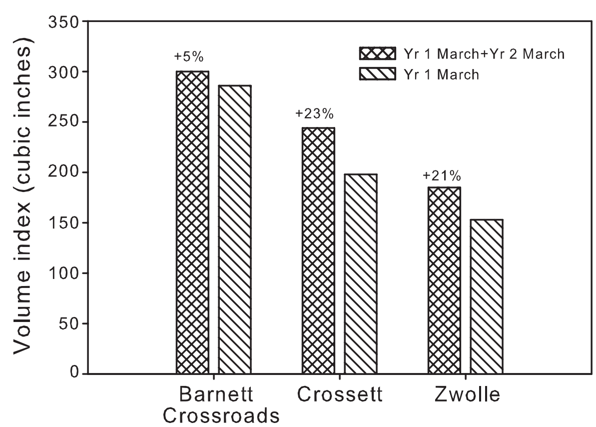

Figure 2—Third year loblolly pine stem volume index for the single first year March (Yr 1 March) and first year March plus second year March (Yr 1 March + Yr 2 March) application of Arsenal® AC plus Oust® herbaceous weed control treatment. Percentages are the gain from the second year application.

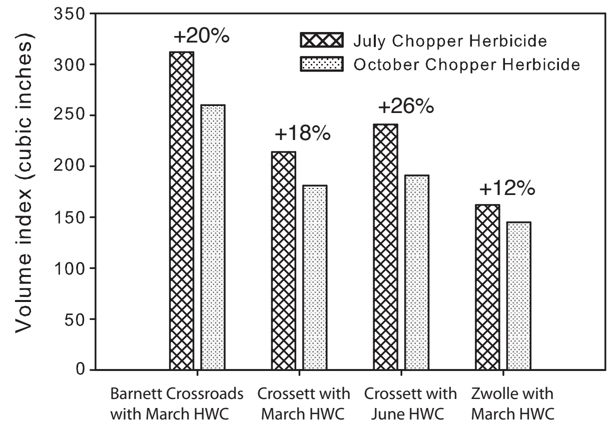

Figure 3—Third year comparison of July and October Chopper® herbicide site prep when used with year 1 herbaceous weed control. Percentages show the gain in loblolly pine stem volume index for the July over the October application timing.

Operational Conclusions

These results indicate that first-year HWC is important on Upper Coastal Plain sites, that earlier season Chopper® herbicide applications should be preferred but is not essential if operational constraints prevent them, and that Chopper® herbicide rates of 48 or 64 ounces per acre provided better pine response than 32 ounces per acre.

COMPARISONS

Herbaceous Control without Herbicide Site Prep

The Barnett Crossroads location included an additional main treatment plot with no Chopper herbicide site prep. The pattern of response to different herbaceous weed control regimes was similar with or without herbicide site prep. However, all herbaceous weed control treatments combined with Chopper® herbicide performed considerably better than those without (fig.

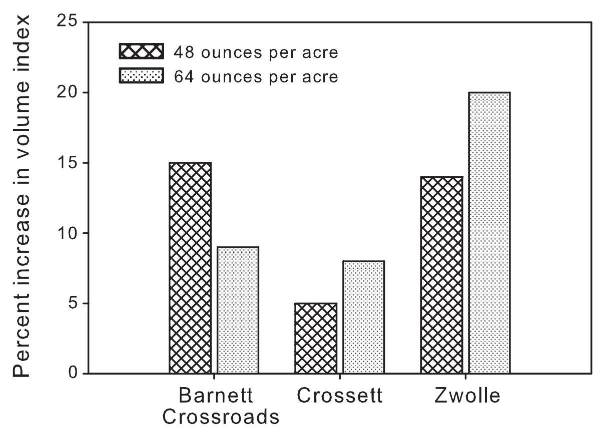

Figure 4—Third year percent increase in stem volume index for the 48 or 64 fluid ounce per acre rate over the 32 fluid ounce per acre rate of Chopper® herbicide.

5). Combining Chopper herbicide site prep with HWC resulted in a synergistic (more than additive) response (fig. 6).

Long-term gains from first year herbaceous weed control treatments depend on the conditions under which they are used. Gains might not be achieved if the treatments do not control established species, germinating species, or are used without previous woody vegetation control. Chopper® herbicide site prep provides a base treatment to control established vegetation prior to HWC. A gradient in quality of vegetation control was observed at Barnett Crossroads (fig. 7) where year 3 volume index was closely related to average total first year cover for site prep treatments with and without year 1 March HWC. Further, of the total percent cover, there was less than 4 percent cover in woody vegetation following chemical site prep and more than 40 percent cover in woody vegetation for treatments without chemical site prep.

Comparing Growth of Operational to Complete Control Studies

Response to vegetation control depends on many factors such as timing and duration of control, level of vegetation that would be present without control, type of competing vegetation (tree, shrub, grass, forb, etc.), and crop tolerance to vegetation control methods. Long-term response research simplified this research problem by estimating maximum potential response to vegetation control using total vegetation control treatments. These long-term studies provide yield estimates under weed free conditions. The study series used for comparison here was more rigorous in understanding stand development in terms of vegetation type and included complete herbaceous control, complete woody control, and complete woody and herbaceous control.

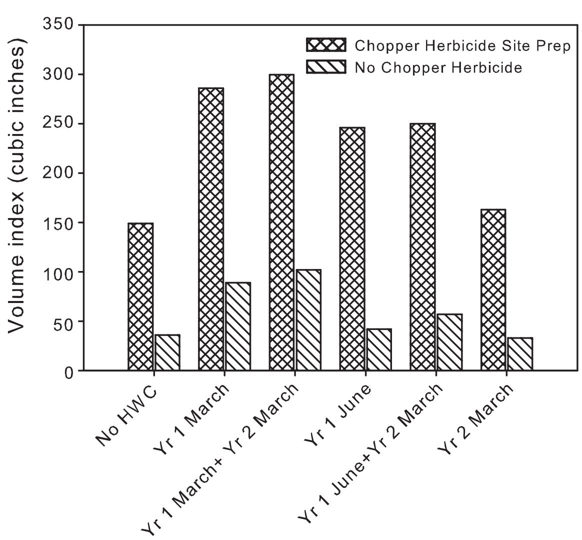

Figure 5—Third year loblolly pine stem volume index compared by herbaceous weed control treatment with and without Chopper® herbicide site prep at Barnett Crossroads, AL. HWC treatments were applications of Arsenal® AC plus Oust® in March or June of the first year (Yr 1) and/or March of the second year (Yr 2).

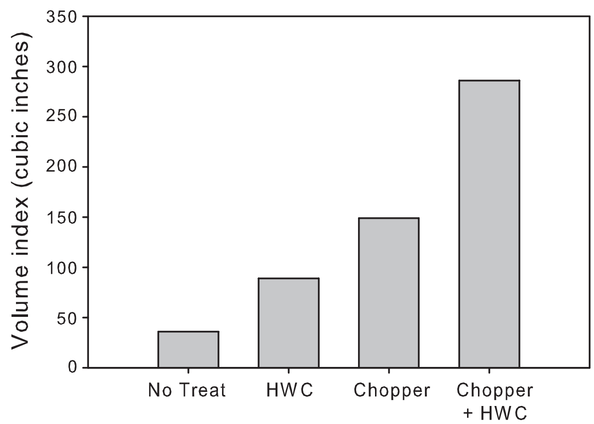

Figure 6—Third year stem volume index at Barnett Crossroads showing a synergistic (more than additive) response to the combined treatment of Chopper® herbicide site prep and HWC. Treatments are rip and bed site prep without additional vegetation control (No Treat), with year 1 March application of Arsenal® AC + Oust® for herbaceous weed control (HWC), with Chopper® herbicide site prep (Chopper), or with both Chopper® and HWC.

Long-term intensive vegetation control studies were intended to provide baseline information by which to judge operational treatments and to judge growth responses in young stands without requiring long-term studies for every potential silvicultural treatment. However, weather patterns, crop tree genetics, nursery practices, and other factors are never constant. Comparisons of "gains" over an untreated check included in both the long-term complete control studies and the younger operational treatment studies will mitigate this problem if gains to vegetation control treatments and these other factors are approximately additive, and are conservative if gains are less than additive.

Treatment definitions—Stand development to complete vegetation control was reported through age 15 by Miller and others (2003). This baseline study included no vegetation control, 4 years of complete herbaceous control, complete woody control, and complete woody and herbaceous control. These treatments are paired with the operational treatments listed in table 3. Operational treatments were one time applications that were most effective based on study results. The woody control operational treatment was 48 ounces per acre July Chopper® herbicide site prep. The herbaceous weed control treatments were either first year March (Barnett Crossroads, Zwolle) or first year June (Crossett) applications of Arsenal® Applicators Concentrate plus Oust®.

Locations compared—The long-term complete control study had eight study locations on Upper Coastal Plain sites. Comparisons were made for the three locations that most closely matched the operational study locations based on soils, competing vegetation, and geographic location. Operational and complete control study locations compared are listed in table 4. Responses are also compared to the average response across all eight Upper Coastal Plain sites.

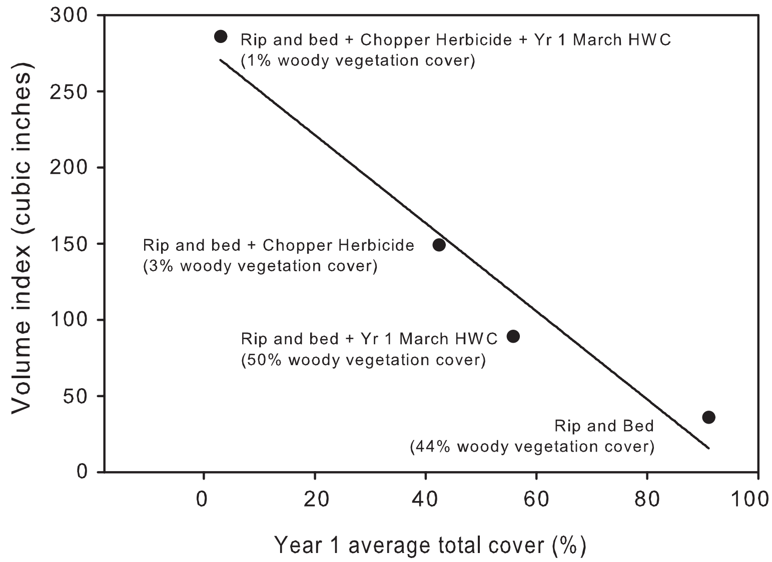

Figure 7—Linear relationship (R-square = 0.96) between third year stem volume index and average first year percent total (woody plus herbaceous) cover of competing vegetation at Barnett Crossroads. Average total cover is average of June and August first year cover assessments.

Comparison of year 3 height gains—Year 3 height gains over the no vegetation control treatment are compared between the operational Barnett Crossroads and complete vegetation control study at Atmore in figure 8. Height gain is used to reduce the effects of factors that differ by study and location. This was only possible for the operational study at the Barnett Crossroads location where all HWC treatments were included without Chopper® site prep. The average gain for all eight Upper Coastal Plain complete control study locations is included for comparison.

The Barnett Crossroads and Atmore locations had similar vegetation of herbs, hardwoods, and gallberry (*Ilex glabra* (L.) Gray.) on similar soils. Year 3 height gains to operational treatments at Barnett Crossroads were similar or greater than gains from complete control treatments at Atmore. Height gain to Chopper® herbicide site prep with HWC at Barnett Crossroads was 4.2 feet compared to 3.1 feet from complete woody and herbaceous control at Atmore. The 3.1 foot year 3 height gain at Atmore equated to an increase of 1 913 cubic feet per acre (121 percent) in year 15 merchantable volume (Miller and others 2003).

Comparison of year 3 heights—The Zwolle and Crossett study locations did not include HWC treatments without herbicide site prep so comparisons of height gains and isolation of the effects of other silvicultural treatments were not possible. Year 3 heights (fig. 9) following operational regimes of Chopper® herbicide site prep with first year HWC compare favorably or exceed year 3 response observed in complete vegetation control research trials.

Table 3—Definition of vegetation control level for complete control and operational treatment research studies

Vegetation control level	Complete control studies	Operational treatment studies
None	No weed control	No weed control
Herb	4 years complete herbaceous control	Year 1 Arsenal® AC + Oust® HWC
Woody	4 years complete woody control	July site prep with 48 ounce/acre Chopper® herbicide
Woody + Herb	4 years complete vegetation control	July site prep with 48 ounces per acre Chopper® and year 1 Arsenal® AC + Oust® HWC

Table 4—Description of study type (operational or complete vegetation control treatments), soil series, mechanical site prep, approximate level of woody vegetation, and planting method by study location

	------------ Alabama ---------------		--------Louisiana--------		---------- Arkansas ----------	
Location	Barnett Crossroads	Atmore	Zwolle	Arcadia	Crossett	Warren
Study type	Operational	Complete	Operational	Complete	Operational	Complete
Soils series	Orangeburg/ eroded Troup	Orangeburg	Kirvin/Sacul	Sacul	Bude	Saffell/Stough
Site prep	Rip and bed	Whole tree chip	Pile only	Chop and Burn	Bed	Chop and Burn
Woody vegetation	Low hardwood, moderate gallberry	Low hardwood, moderate gallberry	Moderate hardwood	Moderate hardwood	Low hardwood	Low hardwood
Planting method	Machine	Hand	Machine	Machine	Hand	Hand

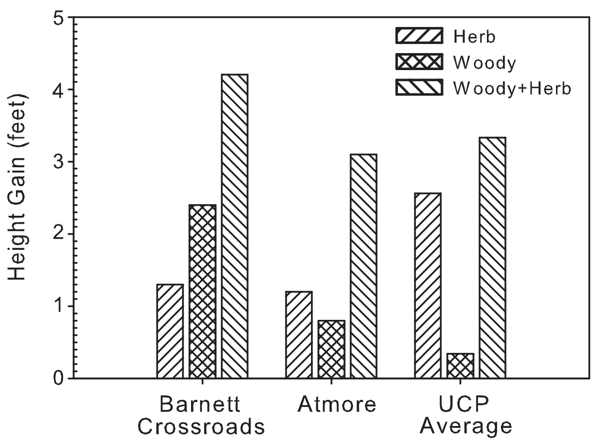

Figure 8—Year 3 loblolly pine height gain (over no vegetation control) for herbaceous, woody, and woody + herbaceous vegetation control for operational treatments at Barnett Crossroads, complete control treatments at Atmore, and complete control treatments averaged across eight Upper Coastal Plain (UCP) sites. Barnett Crossroads and Atmore locations had similar vegetation types. Operational woody control was Chopper® herbicide site prep. Operational herbaceous control was one first year Arsenal® AC plus Oust® application. Complete control was 4 years of complete woody control, complete herbaceous control, or both.

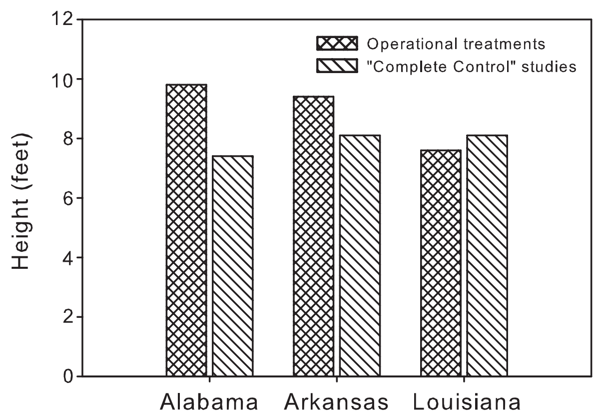

Figure 9—Year 3 loblolly pine height for woody plus herbaceous vegetation control treatments for paired operational and complete control studies. Operational woody control was Chopper® herbicide site prep. Operational herbaceous control was one first year Arsenal® AC plus Oust® application. Complete control studies had 4 years of complete woody control or complete woody and herbaceous control.

CONCLUSION

Examination of 36 different treatment regimes on Upper Coastal Plain sites determined that gains can be made by selecting the rate and timing of Chopper® herbicide and the timing of herbaceous weed control. July Chopper® herbicide applications performed better than October applications. Chopper® herbicide rates of 48 or 64 ounces per acre performed better than 32 ounces per acre. First year HWC was more important than second year HWC but combining first and second year HWC increased growth. Pine response to March HWC was better than June HWC at two of three locations. On a poorly drained silt-loam soil with high water table in Arkansas, June HWC was better than the more traditional March timing.

Operational vegetation management treatment regimes can be used to achieve pine response that either exceeds or compares favorably with pine response observed in intensive vegetation control research trials. The operational treatment used for comparison was an operational rate of Chopper® herbicide site prep with one herbaceous weed control treatment. This treatment regime was effective because it provided high quality vegetation control of both woody and herbaceous vegetation and provided the same synergistic response observed in intensive vegetation control trials when both woody and herbaceous vegetation were completely controlled.

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EVALUATING SUBSOILING AND HERBACEOUS WEED CONTROL ON SHORTLEAF PINE PLANTED IN RETIRED FARM LAND[1]

John D. Kushla[2]

Abstract—In March 2005, shortleaf pine was planted on retired fields of the Mississippi Agriculture and Forestry Experiment Station in Holly Springs. The objectives were to evaluate subsoiling and herbaceous weed control on first year seedling stocking, survival, and size. First year seedling measurements were made on stocking, survival, and size. Only results for first year seedling survival will be reported here. Subsoil tillage, herbaceous weed control, and control treatments were completed. Treatments were replicated 3 times in a randomized complete block design. The subsoiling treatment was done in December of 2004. The herbaceous weed control treatment was 4 ounces Arsenal AC® + 2 ounces Oust XP® per sprayed acre applied in a 4-foot band over the row in April 2005. In addition, mowing was completed 3 times between rows during the first growing season. Measurements were conducted on a 0.1-acre plot within each treatment. Neither subsoiling nor herbaceous weed control had any significant effect on seedling survival the first year.

INTRODUCTION AND PROBLEM

Loblolly pine is the premier species of the southern pines. It has an extensive range across the southern United States and is very adaptable to a wide variety of soil and site conditions (Schultz 1997). Loblolly pine is relatively easy to regenerate, has been genetically improved for decades (McKeand and others 2003), and responds well to intensive management (Stanturf and others 2003a, 2003b).

Martin and Shiver (2002) reported that first generation improved loblolly contributed to 11-16 percent better volume growth on a Coastal Plain site and 12-19 percent better volume growth in the Piedmont. Early plantations were established primarily with mechanical site preparation and burning. With the increasing production of fertilizers in the mid twentieth century, forest research found that both loblolly and slash pines were very responsive to added nutrients. Diagnostic tools based on site (Kushla and Fisher 1980, Fisher and Garbett 1980) and foliar analyses were developed (Wells and Allen 1985). In addition to fertilizers, the application of herbicides to control competing vegetation had pronounced effects on loblolly plantation growth. Pine volumes at age 5 more than doubled with total herbaceous weed control and improved by 67 percent with total woody control (Miller and others 1995a, 1995b). However, beyond age 6, total woody control exerted greater influence on pine volume by age 11 on a Georgia site than herbaceous weed control (Zutter and Miller 1998). Furthermore, regional studies that evaluated the effects of total vegetation control and frequent fertilizer applications on loblolly plantation growth revealed additive effects. Volume growth responses were in the range of two to four times that of controls with repeated fertilizer and herbicide application (Borders and Bailey 2001, Jokela and others 2004, Martin and Jokela 2004). Meanwhile, tillage studies particularly subsoiling on Piedmont and Upper Coastal Plain soils have continued, but with mixed results. Wheeler and others (2002) found that tillage, including subsoiling, improved seedling survival and stand volume growth after 3 years.

By contrast, research with shortleaf pine has been eclipsed by loblolly. Much research on shortleaf pine has focused on management of natural stands (Baker and others 1996). Some research has been done evaluating responsiveness of natural shortleaf stands to thinning (Cain 1996) and vegetation control (Cain 1991). Yet given the very extensive range of shortleaf pine, and its tolerance to dry, infertile sites (Lawson 1990), shortleaf pine is a viable choice for plantation management in northern Mississippi. Here loblolly pine approaches the northern extent of its range, and is prone to ice damage from periodically severe winter storms (Baker and Langdon 1990). Further evaluation of shortleaf pine to intensive forest management including site preparation, vegetation control, and fertilizer application is warranted.

METHODS

Recently, shortleaf pine plantations were established on the Mississippi Agriculture and Forestry Experiment Station at Holly Springs, MS. Subsoil tillage treatments were done prior to planting in December 2004 using a 20-inch ripping shank pulled by a tractor on ten foot planting centers. Shortleaf pine was then planted on the retired farmland in March 2005 at a nominal density of 622 trees per acre.

The herbaceous weed control (HWC) treatment consisted of a combination of herbicide application and mowing for the first year. Herbicide was applied in April of 2005. A tank mix of 4 ounces Arsenal AC® and 2 ounces of Oust XP® per acre was applied over the planted trees in a four-foot band. In addition, row centers were mowed three times during the growing season on treated areas.

All treatments (tillage, herbaceous weed control, and control) were replicated three times in a randomized complete block design. First year measurements were taken January through March 2006. Seedling measurements included stocking, mortality, survival (as a percent), total height, and root collar diameter. Only results for survival are reported here. Measurements were done on 4, 1/40-acre subplots

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within each treatment and replication, and compiled into one measurement (for a 0.1-ac plot) for analysis.

RESULTS

First year seedling survival by treatment is presented in Table 1. Survival on the control treatment (no subsoil tillage or HWC) was 90.1 percent. Subsoil tillage improved first year survival about 1 percent, HWC improved survival about 3-4 percent. The best survival was on the combination of subsoil tilled and HWC at 94.4 percent. The analysis of variance is shown in Table 2. There were no significant ($\alpha = 0.05$) effects due to blocking, subsoil tillage, or HWC. There was a significant interaction between subsoil tillage and HWC.

DISCUSSION

Schilling and others (2004) found little improvement of loblolly growth on subsoiled Upper Coastal Plain and Piedmont sites. This may indicate that such treatments are more site-specific. Indeed, the retired farmland on which the shortleaf were planted was cropped, not grazed. In addition, the trees in this study were machine planted. The tree planter had a coulter shank nearly as long as the ripping shank. Finally, since ripping was done late in the year, the seedlings were not planted directly into the rip, but alongside. Occasionally, the tree planters did not closely follow the subsoil trenches.

The region wide competition studies with loblolly pine revealed that pine volumes at age 5 more than doubled with total herbaceous weed control (Miller and others 1995a, 1995b). However, given the previous cropping history to this site, grass competition was not uniform. Much of the planting sites were dominated by seasonal forbs, which apparently did not as severely impact seedling survival.

Further evaluations of this data will examine subsoiling and herbaceous weed control effects on seedling size (diameter and height). In addition, a second-year application of herbicide will be added as another factor level. Future research on these shortleaf plantations will entail their response to fertilizer applications and thinning.

Table 1—Response matrix of first year survival to subsoiling and herbaceous weed control

Average first year survival		
	Herbaceous weed control	
Subsoil tillage	Control	Treated
	- - - - - - - - - - - *percent* - - - - - - - - - - -	
Control	90.1	93.9
Treated	91.4	94.4

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Table 2—Analysis of variance for treatment effects

Source	d.f.	SS	MS	F
Total	11	152.069		
Block	2	44.662	22.331	1.931 NS
Subsoil	1	2.521	2.521	0.218 NS
Herbaceous Weed Control (HWC)	1	35.021	35.021	3.030 NS
Subsoil x HWC	1	0.521	0.521	0.045 NS
Error	6	69.345	11.558	

d.f.= degrees of freedom
SS = sum of squares
MS = mean square error
F = Fvalue
NS—not significant
*--significant at α=0.05

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EFFECTS OF DISKING, BEDDING, AND SUBSOILING ON SURVIVAL AND GROWTH OF THREE OAK SPECIES IN CENTRAL MISSISSIPPI

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Abstract—A replicated split-plot design experiment to evaluate the effects of three site preparation methods (disking, bedding, and subsoiling plus bedding) on survival and growth of three oak species (cherrybark, *Quercus pagoda* Raf.; Shumard, *Quercus shumardii* Buckl.; and Nuttall, *Quercus texana* Buckl.) was established in 1994 in Madison County, MS. The study site was an abandoned agricultural field on a terrace of the Pearl River consisting of poorly drained, fragipan soils often saturated during wet periods and winter months. Differences among species for first and tenth year survival were statistically significant and were 92 and 79 percent for Nuttall, 95 and 66 percent for Shumard, and 85 and 60 percent for cherrybark. Tenth year diameter at breast height (d.b.h.) and height trends were similar for the three species within site preparation methods. Nuttall outperformed cherrybark and Shumard, but showed no significant differences for site preparation methods. In the driest replication, cherrybark and Shumard significantly benefited from the subsoiling plus bedding treatment, but bedding was not consistently significantly different from disking. It is believed that the use of a D6 Caterpillar® bulldozer and Symonds Blade Plow may have had a negative impact on soil compaction and growth in the two wettest replications.

INTRODUCTION

In recent years, there has been an increasing trend in the conversion of abandoned agricultural land to forestland in the Southern United States (Munn and Evans 1998). Data compiled for the 1992 Resource Planning Act by the USDA Forest Service Forest Inventory Analysis (FIA) indicates that 5.7 percent of agricultural land was converted to forestland in the southern region between 1984 and 1992. This was the largest conversion of land from one use to another reported in the study. Twenty-five million acres of cropland in the Southeastern United States is estimated to be converted to some type of forest land by the year 2040 (Wear and Greis 2002), and the potential for these sites to be afforested with hardwoods is considerable (Ezell and others 2007). Seedling quality, planting quality, species suitability to soil and site type, site preparation, and herbaceous weed control are important factors that must be addressed to insure hardwood seedling survival and adequate growth.

Cropland preparation, prior to the introduction of no-till planting equipment, was typically done by plowing, disking, and dragging with a tractor each spring before planting. These site preparation techniques increase soil compaction and lead to the development of plow pans. The presence of these pans and naturally occurring fragipans can restrict deep root development and drainage creating poor conditions for woody crop establishment. Soil compaction resulting from machine traffic can decrease soil aeration porosity and reduce root growth, water and air movement, and solute diffusion (Scott and others 2004). Ezell and Shankle (2004) observed a significant increase in first year height and groundline diameter of Shumard oak (*Quercus shumardii* Buckl.), water oak (*Quercus nigra* L.), willow oak (*Quercus phellos* L.), and green ash (*Fraxinus pennsylvanica* Marsh.) species from subsoiling a retired agricultural site. Fallis and Duzan (1994) reported an increase from the effects of subsoiling on soils with big stone and fragment content on initial survival and 19 year height and basal area of loblolly pine (*Pinus taeda* L.).

The objective of this study was to analyze the effect of disking, bedding, and subsoiling plus bedding on the survival and growth of four commercially important oak species planted on a typical poorly drained retired agricultural field in central MS.

MATERIALS AND METHODS

The study was established in 1994 on a 63 acre farm that was donated to Mississippi State University through the John and Jane Player Endowment. The land is situated on a terrace in the Pearl River bottom in Madison County, MS. This area, typical of rural MS, was homesteaded and farmed for decades before retirement. The silty loam textured Bude and Providence soils series (Scott 1984) of the study site possess fragipans and along with the site's agricultural history are characteristic of many bottomland agricultural sites in MS. Fragipan depth was measured with a penetrometer and varied among the fields. Three study replications (labeled one, two, and three) were selected to account for differences in fragipan depth and extent plus year round soil moisture. The fragipan in replications one and two extended 23 inches from the surface to 60 inches deep, and the fragipan in replication three extended 19 inches from the surface to 31 inches deep. Replication one was considered the wettest area; replication two was slightly elevated and was the driest area; and replication three was intermediate in soil moisture. On this relatively flat site (0 to 2 percent slope), the fragipans restrict drainage causing soil saturation in the winter or wet periods in addition to presenting a physical barrier to root penetration. The site is not subject to regular inundation from flood waters.

The study was installed as a replicated split-plot design with site preparation methods representing main plots and species representing sub-plots. Main plot site preparation methods consisted of disking (D), bedding (B), and subsoiling plus bedding (SB). Prior to implementing the three site preparation treatments, the entire site was disked to help

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control competing vegetation. Site preparation treatments on the main plots were applied in blocks of rows that were 13 feet apart on centers and were randomly assigned within a replication. A disk harrow, bedding plow, and Symonds Blade Plow pulled by a D6 Caterpillar® bulldozer were used to apply the D, B, and SB treatments, respectively. The blade plow, manufactured by Symonds Australia, Inc., cut a subsoil trench 30 inches deep and mounded beds 18 inches high directly over the trench. Soil was neither extremely dry nor wet during the October site preparation.

Nuttall (*Quercus texana* Palmer), water, Shumard, and cherrybark (*Quercus pagoda* Raf.) 1-0 oak seedlings were acquired from Scott Paper Company's (now Molpus Timberland) nursery in Elberta, AL, and planted in January 1994 with planting shovels in randomized species subplots within main plot site preparation blocks. These species were selected because of their commercial value and differences in drainage preference. Water oak seedling roots were dry upon arrival from the nursery, and this resulted in poor survival and their ultimate removal from the study. Seedling root collar diameters and heights were not measured prior to planting, but seedlings were sorted across species for comparable size. A total of 804 cherrybark, Shumard, and Nuttall seedlings were planted on 13 by 13 foot spacing in three species blocks per three site preparation plots per three replications, approximately 30 trees per species block. The number of trees planted varied slightly across replications one, two, and three (279, 288, and 237) because of the irregular shape of the old agricultural fields. There were no prolonged dry periods during the 1994 growing season, and moisture conditions were deemed adequate for survival.

Herbaceous weed control was performed manually using directed spray from backpack sprayers prior to planting and every year following planting. Beds were treated with 4 pounds active ingredient per acre Simazine® each year during the 10 year study period in late January/early February to inhibit the germination of weed seed. During the growing season, competing vegetation was controlled with 48 ounces of Roundup® per acre in four foot strips within rows. Areas between rows were mowed several times during the growing season.

Differences among replications, site preparation methods, species, and interaction terms for first year survival (taken at the beginning of the second growing season) and tenth year survival, d.b.h. and height were analyzed with SAS GLM (SAS 1999) using a completely fixed effect, replicated split-plot model. An arcsine transformation was applied to subplot mean percent survival data. In addition to an analysis of variance of the entire study design, separate analyses were conducted by individual study replications, site preparation methods, and species.

RESULTS AND DISCUSSION

Survival

Species differed significantly for both first year and tenth year survival (table 1). First year survival averaged across replications and site preparation methods ranged from 85 percent for cherrybark and 92 percent for Nuttall to 95 percent for Shumard. Tenth year survival ranged from 60 percent for cherrybark and 66 percent for Shumard to 79 percent for Nuttall. Neither species-by-site preparation method nor species-by-replication interactions were significant. The replication-by-site preparation method interaction was significant for first year survival only. Analysis of variance by replication did not reveal any patterns that could be explained on the basis of replication wetness or the effect of site preparation method on soil moisture.

First year survival for the three hardwood species was comparable to that reported in a study of the effects of herbaceous weed control on oak seedling survival (Ezell and others 2007). Ezell and others (2007) demonstrated a 20 to 44 percent increase in first year oak seedling survival in herbicide treatment areas versus non-treatment areas. The complete control of competing vegetation in our study may have had more influence on first year survival than treatments that related to soil moisture. Some rodent and mechanical damage was noted between years one and ten, but it was scattered in occurrence and minimal. After 10 years, there were still no significant survival differences due to site preparation methods or replications. Cherrybark, which prefers the better-drained bottomland soils of the three species (Harlow and others 1979), exhibited the lowest tenth year survival at 60 percent (a loss of 25 percent from first year survival). Nuttall, known for rapid growth on poorly drained clay soils (Hardin and others 2001), had the highest survival at 79 percent (a loss of 13 percent from first year survival). Shumard, which is usually found on terraces in minor stream flood plains (Hardin and others 2001), had a tenth year survival of 66 percent (a loss of 29 percent from first year survival).

Tenth Year D.b.h. and Height

All first-order and second-order interaction terms for replications, site preparation methods, and species were significant for tenth year d.b.h. and height (table 1); therefore, separate analyses were conducted for each factor and level. The significant interaction terms imply that the differences among species for d.b.h. and height vary with site preparation method and replication. Average diameters and heights for the separate analyses and their significance are given in table 2. The expected response was an increase in d.b.h. and height on the wettest replication (one) as the intensity of site preparation increased from D to SB and a diminishing difference as the replications decreased in wetness.

Table 1—Analysis of variance[a] for first year survival and tenth year survival, d.b.h., and height variables in the replicated split plot design site preparation method-oak species study in Madison County, MS, where site preparation methods are main plots and species are subplots

		Measurement traits							
		First year survival (%)[b]		Tenth year survival (%)[b]		Tenth year d.b.h. (in)		Tenth year height (ft)	
Source of variation	DF	MS	F-test [cd]	MS	F-test[cd]	MS	F-test [cd]	MS	F-test [cd]
Replication (Rep)	2	0.046	3.27	0.075	1.76	9.56	7.92**	406.36	22.82**
Site prep (SP)	2	0.008	0.55	0.006	0.14	1.36	1.13	5.05	0.28
Rep x SP	4	0.092	6.56**	0.010	0.24	14.08	11.67**	218.79	12.29**
Species (SC)	2	0.065	4.68*	0.188	4.38*	77.73	64.42**	1184.91	66.55**
Rep x SC	4	0.007	0.50	0.077	1.79	3.47	2.88*	85.15	4.78**
SP x SC	4	0.021	1.51	0.030	0.71	5.78	4.79**	104.42	5.86**
Rep x SP x SC	8					3.47	2.88**	111.09	6.24**
Error	528					1.21		17.81	
Error (subplot)[b]	8	0.014		0.043					

[a] Model is completely fixed effects.
[b] Survival was calculated on a percentage of subplot means using the arcsine transformation.
[c] * = significant at the 0.05 level.
[d] ** = significant at the 0.01 level.

The three species yielded similar trends across site preparation method-by-replication combinations; however, differences among means were not always significant. In general on the two wettest replications (one and three), d.b.h. and heights were lower for the SB treatment than for the less intensive D and B treatments. Cherrybark d.b.h. and height were significantly lower (table 2) for the SB treatment. Cherrybark averaged 4.2 inches d.b.h. and 24.6 feet in height for the D treatment and 2.2 inches d.b.h. and 15.5 feet in height for the SB treatment. Even though soils were not noticeably wet during site preparation, the weight and soil disturbance of the D6 Caterpillar® bulldozer and Symonds Blade Plow used to implement the SB treatment may have compacted soils, compared to the D and B treatments. Compaction could have contributed to lower SB treatment growth.

Significant differences in cherrybark and Shumard d.b.h. and heights for the driest replication (two) support the expected response of increased growth with increasing site preparation intensity. Bedding alone (B) did not always give a significant increase in growth over disking (D), but subsoiling and bedding (SB) provided a 39 percent d.b.h. and 37 percent height increase over disking (D) for cherrybark (table 2). If soil compaction were a factor in growth, the weight and soil disturbance of the bulldozer and blade plow may have had less of an effect on the drier replication. Significant differences for Shumard occurred only in replication two. The SB site preparation treatment outperformed the D (by 45 percent d.b.h. and 39 percent height) and B (by 14 percent d.b.h. and 19 percent height) treatments.

Height means among site preparation methods were significantly different for Nuttall in replication three (intermediate in wetness), but the differences among site preparation means were very small. This result can be explained by Nuttall's unusually high survival in this replication and the subsequent higher degrees of freedom in the denominator of the F-test. In general, tenth year Nuttall d.b.h. and height were not significantly affected by site preparation method or replication.

Table 2—Tenth year average diameter and height by study replication (Rep), species, and site preparation method for three oak species planted in Madison County, MS

Rep	Pan depth/ wetness	Oak species	Site preparation method[a]	Tenth year average d.b.h (in)[bc]		Tenth year average Height (ft)[bc]	
1	23-60 in Wettest	Cherrybark	D	4.2	A	24.6	A
			B	3.8	A	22.9	A
			SB	2.2	B	15.5	B
			Combined mean	3.7**		22.4**	
		Shumard	D	3.9		21.4	
			B	3.6		23.3	
			SB	3.6		22.5	
			Combined mean	3.7		22.5	
		Nuttall	D	5.4		27.6	
			B	4.8		26.1	
			SB	4.8		27.6	
			Combined mean	5.0		27.1	
2	23-60 in Driest	Cherrybark	D	3.1	A	18.1	A
			B	3.9	B	21.0	A
			SB	4.3	B	24.8	B
			Combined mean	3.7**		21.0**	
		Shumard	D	2.9	A	17.9	A
			B	3.7	A	21.7	B
			SB	4.2	B	25.9	C
			Combined mean	3.6**		21.2**	
		Nuttall	D	4.8		25.1	
			B	4.2		22.7	
			SB	4.6		23.9	
			Combined mean	4.6		24.1	
3	19-31 in Intermediate	Cherrybark	D	3.2	B	18.6	
			B	4.0	A	20.8	
			SB	2.9	B	18.0	
			Combined mean	3.4*		19.0	
		Shumard	D	3.0		18.7	
			B	3.3		17.8	
			SB	2.7		17.1	
			Combined mean	2.9		18.0	
		Nuttall	D	4.6		24.9	A
			B	4.2		23.0	B
			SB	4.3		24.3	AB
			Combined mean	4.4		24.1*	

[a] Site preparation method: D = disked, B = bedded, and SB = subsoiled and bedded.
[b] * = significant at the 0.05 level; ** = significant at the 0.01 level; indicates significant differences among site preparation methods within species and replication.
[c] A, B, C = Duncan's multiple range test groupings; means with the same letter are not significantly different.

CONCLUSIONS

Nuttall oak planted on a poorly drained retired agricultural field in a river bottom terrace in Madison County, MS, was superior in tenth year survival and growth to cherrybark and Shumard oaks. Nuttall d.b.h. and height means were not significantly different for disking, bedding, or subsoiling plus bedding site preparation treatments, but it performed well in all three replications that varied in degree of year round wetness. Differences among species for first and tenth year survival were statistically significant and were 92 and 79 percent for Nuttall, 95 and 66 percent for Shumard, and 85 and 60 percent for cherrybark. First year survival varied significantly for site preparation method-by-replication but not in a pattern that could be readily explained by species soil moisture preference or drainage improvement.

Tenth year d.b.h. and height growth trends for site preparation methods were similar for the three species. In the driest replication, cherrybark and Shumard significantly benefited from the subsoiling plus bedding (SB) treatment, but bedding (B) was not consistently significantly different from disking (D). The principal effect of the subsoiling plus bedding (SB) treatment on d.b.h. and height may have been largely due to subsoiling, since the bedding (B) alone treatment was only sometimes significantly different from disking (D).

In the wettest replication, disking (D) was superior to bedding (B) and subsoiling plus bedding (SB), but cherrybark was the only species where d.b.h. and height were significantly different for the treatments. This ranking of site preparation methods was opposite to that in the driest replication. It is believed that the use of a D6 Caterpillar® bulldozer and Symonds Blade Plow to implement the SB treatment may have had a negative impact on soil compaction and growth in the two wettest replications.

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EVALUATION OF NUTTALL OAK AND CHERRYBARK OAK SURVIVAL BY PLANTING STOCK AND SITE PREPARATION TREATMENT TYPE IN A WRP PLANTING ON A RETIRED AGRICULTURAL SITE

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Abstract—Oaks are an ecologically and economically important component of the southern landscape, and many landowners are opting to regenerate their lands with these species. Federal cost share programs, such as the Wetland Reserve Program (WRP), have increased public interest in afforestation of retired agricultural sites in the Lower Mississippi Alluvial Valley (LMAV). Acorns, bare-root, container, and potted seedlings of Nuttall oak (*Quercus texana* Buckl.) and cherrybark oak (*Quercus pagoda* Raf.) were tested in a WRP planting near Port Barre, LA to evaluate survival following four mechanical/chemical site preparation combinations. These acorns/seedlings were planted using a 16 by 36 foot spacing with soft mast tree species interplanted on 16 by 9 foot intervals to meet WRP compliance specifications. The entire research site was subsoiled on 16 foot centers with acorn/seedlings planted in the subsoil trench. Control (no mechanical/chemical treatment), subsoil only, subsoil/Chopper EC®, subsoil/Arsenal AC®, and subsoil/OneStep® site preparation treatments were applied in an attempt to evaluate which treatment combination provided the greatest overall survival. Survival and herbaceous coverage estimates were recorded monthly in order to chronologically observe site preparation efficacy and the relationship between herbaceous competition and oak survival. Acorns did not germinate and bare-root seedlings exhibited very low survival. Containerized seedlings exhibited midrange survival and potted seedlings had the greatest overall survival. Early season flooding and a summer drought probably decreased survival of all planting stocks. Increased broadleaf competition in areas that received chemical treatments resulted in less survival compared to areas that received subsoiling only.

INTRODUCTION

Oaks (*Quercus* spp.) are an ecologically and economically important component of the southern landscape, and many landowners are opting to regenerate their lands with these species. Federal cost share programs, such as the Wetland Reserve Program (WRP) and the Conservation Reserve Program (CRP), have increased public interest in afforestation of retired agricultural sites in the Lower Mississippi Alluvial Valley (LMAV). These programs offer financial incentives to aid in recovery of costs incurred by artificially regenerating oaks (Schweitzer and Stanturf 1999).

According to Schoenholtz and others (2001), survival of planted seedlings and acorns has been low in these areas, resulting in a low percentage of oaks in established stands. This is possibly a corollary of poor soil conditions, poor planting techniques, poor seedling quality, and problems with competing vegetation. These problems can be alleviated through proper planting of high quality seedlings and through the application of proper silvicultural treatments needed to achieve enhanced survival and growth.

Survival and growth of seedlings could potentially be improved by using both mechanical and chemical site preparation treatments. Many retired fields have substantial levels of compaction due to past land use practices (Allen and others 2001). Subsoiling can correct some of the problems associated with these sites. Subsoiling can increase growth and possibly survival (Ezell and Shankle 2004). Potential increases in survival and growth from subsoiling can be the result of improved moisture and nutrient uptake, as well as enhanced root formation. These advantages could be critical on more xeric sites. Possibly the most influential agent in the failure of oak plantings is competing vegetation, and an increase in first-year growth of oaks receiving herbicide treatments for competition control has been documented (Russell and others 1997). Both herbaceous and woody competition may pose a threat to the survival of planted oak seedlings, with herbaceous competition posing the greatest threat in the first years of establishment (Smith and others 1997). Improved oak survival as a response to herbicide applications has been noted in several studies (Ezell and Catchot 1997, Ezell and Hodges 2002).

OBJECTIVES

The objectives of the study were:

1. To evaluate effects of subsoiling on first-year survival in oaks.
2. To evaluate effects of competition control on first-year survival of oaks.
3. To evaluate first-year survival of different planting stock types.

MATERIALS AND METHODS

Site Description

The tract selected for this study was formerly in row-crop production and is located approximately five miles northeast of Port Barre, LA in St. Landry Parish. Watercourses border the site on all sides. The study area encompasses approximately 78 acres within a 250-acre retired agricultural field. Soil series are Sharkey clays, and the average yearly precipitation is 53.56 inches. Soil saturation was observed on much of the study area through early June 2005, but by October, cumulative precipitation was 16.58 inches lower than average for the area.

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There was a well established herbaceous groundcover with a scattered woody component at the time of site selection. The dominant herbaceous species onsite included: vaseygrass (*Paspalum urvillei* Steud.), sumpweed (*Iva annua* L.), bermudagrass (*Cynodon dactylon* L.), beaked rush (*Rhynchospora corniculata* Lam.), soft rush (*Juncus effusus* L.), curly dock (*Rumex crispus* L.), and Pennsylvania smartweed (*Polygonum pensylvanicum* L.). Other herbaceous species were present in small quantities. The dominant woody species on the site was tallowtree (*Sapium sebiferum* L.). There were also small components of green ash (*Fraxinus pennsylvanica* Marsh.), black willow (*Salix nigra* Marsh.), sugarberry (*Celtis laevigata* Willd.), eastern baccharis (*Baccharis halimifolia* L.), honeylocust (*Gleditsia triacanthos* L.), and sweetgum (*Liquidambar styraciflua* L.).

Study Design and Plot Establishment

Operational constraints strongly influenced the design of this study. Herbicide treatments, planting stocks, and species could not be randomly allocated for reasons of equipment and personnel efficiency. A split, split strip-plot design was utilized in this experiment. The research was conducted on a rectangular area of approximately 72 acres. This area was divided in a vertical (north/south) direction into four, 18-acre blocks. These blocks were established for the purpose of applying site preparation treatments. For replication purposes, the site was divided horizontally (east/west) into three, 24-acre blocks. A total of 48 data cells comprising 1.5 acres each, were established on the research site. Six control (no site preparation, no herbicide application) data cells were established immediately adjacent to study area boundaries. These data cells were used to determine survival of seedlings in areas without chemical or mechanical silvicultural treatment. All exterior and interior boundary lines were delineated using a transit and a 300-foot surveyor's tape.

Data cell corners were marked with five foot sections of one inch PVC pipe. Individual tree rows were marked with two foot sections of one inch PVC pipe. Tree row pipes were also marked with 36-inch pin flags color specific to species. Individual tree/acorn planting locations were determined and marked with 36-inch pin flags color specific to species.

Site Preparation Treatments

Both mechanical and chemical treatments were used in initial site preparation efforts. Mechanical site preparation consisted of subsoiling the entire area using 16-foot spacing across the site. This subsoiling treatment was performed to reduce "restriction layers" or compaction commonly found in retired agricultural fields. Subsoiling was also utilized to evaluate its effect on survival in oak establishment attempts. The subsoil treatment was performed using a three-inch-wide single shank subsoil plow pulled by a skidder. The subsoil plow was tipped with an eight-inch tiger wing tip followed by two sixteen-inch closing wheels attached to the rear. Subsoil trenches were installed on December 1 and 2, 2004.

There were four chemical site preparation treatments used in this study: a no herbicide application, a 32-ounce Chopper EC® per acre + one percent volume/volume (v/v) Timbersurf 90®, a 16-ounce Arsenal AC® per acre + one percent (v/v) Timbersurf 90®, and a 16-ounce OneStep® per acre + one percent (v/v) Timbersurf 90®. All chemical treatments were applied to the areas which had received the mechanical subsoiling treatment. Chemical site preparation was deemed necessary for the site due to complete herbaceous coverage. Site preparation herbicides were applied using 20 gallons per acre (g.p.a.) total spray volume. Applications were completed using a cluster nozzle sprayer with a radiarc nozzle system and 0.048 tips. This sprayer was mounted on an agricultural tractor and the spray rate was regulated by speed. All chemical site preparation treatments were applied on July 26 and 27, 2004 during morning and evening hours to avoid wind drift.

Seedling Establishment

There were 14 subsoil trenches in each data cell. These served as planting rows with the two outside rows being used as buffers (no measurements). The 12 internal rows were specified as evaluation rows. Individual oak seedling/acorn planting sites were spaced using a 36-foot interval along the subsoiled row. Nuttall oak and cherrybark oak seedlings/acorns were planted. Four planting stock types were used: acorns, bare-root seedlings, containerized seedlings, and potted seedlings. A total of 5,616 seedlings/acorns were planted. Twelve-inch-diameter holes were augered for seedlings planted on potted or bare-root stock rows. The purpose of this augering treatment was to facilitate planting of the large root systems of the potted and large caliper bare-root seedlings. These holes were backfilled to a depth that placed individual seedling root collars at or slightly below ground level. Seedlings were then placed in their respective holes and the holes were refilled with soil being packed around the root systems. Containerized seedlings were planted at or slightly below root collar depth using planting shovels. Acorns were planted approximately one half to one inch deep using a piece of PVC pipe to open a hole, placing the acorn in the hole, and then packing soil over the acorn.

Potted and containerized seedlings were purchased from Five Oaks Tree Nursery in Dewitt, AR and were lifted December 16, 2004. These seedlings were planted on December 18 through 20, 2004. Bare-root seedlings were purchased from Delta Wildlife Consulting, Inc. in Winnesboro, LA and were lifted December 27, 2004. These seedlings were planted on December 28 and 29, 2004. Acorns were purchased form the Louisiana Forest Seed Company, and were collected from sources within LA. The acorns were float tested and guaranteed 95 percent sound. Acorns were planted April 8, 2005. Bare-root green ash, winged elm (*Ulmus alata* Michx.), red maple (*Acer rubrum* L.), hackberry (*Celtis occidentalis* L.), common persimmon (*Diospyros virginiana* L.), and sweetgum seedlings were interplanted between oak seedlings/acorns on nine foot intervals to achieve WRP tree number specifications. These seedlings were not measured, nor assessed for this study.

Survival Observations

Survival checks and herbaceous coverage percentages were recorded monthly from May 2005 through August 2005. A survival check was not completed during the month of September due to complications arising from Hurricane

Katrina. No observable onsite damage resulted from Hurricane Katrina. One half of the treatment and control plots were observed in the monthly evaluations in a checker-board pattern for a total of 27 data cells and 2,808 planting sites evaluated. Seedling survival was based on ocular evaluation. If a seedling was not present it was considered dead. If it was observed as a resprout in later observations, it was included in earlier survival estimations. The cambium was nicked on seedlings which appeared dead to ensure survival status. Acorn germinants were sought, but not found throughout the growing season. Herbaceous ground coverage was estimated ocularly and recorded as a percentage. Herbaceous components were separated into grass or broadleaf categories and then further delineated into major species. Final observations were taken October 8 through 18, 2005 on surviving seedlings.

Data Analysis

Survival averages were calculated using Statistical Analysis System (SAS) software version 9.1®. All survival data were averaged among chemical site preparation treatments, species, and planting stock types. When significant differences were noted among combinations, seedlings were pooled within their respective site preparation treatment, species, and planting stock categories for calculating averages.

RESULTS

Survival/Planting Stock

No acorn germinants were found across the site. Willoughby and others (1996) state that growing season flooding can result in failure of direct seeding attempts. Saturated soil conditions observed onsite from April through June 2005 probably resulted in the failure of acorn germination. Potted seedlings exhibited the best survival, followed by containerized seedlings and bare-root seedlings (table 1). Overall survival of potted seedlings was 31.8 percent greater than containerized seedlings (82.0 percent and 50.2 percent, respectively). Bare-root survival (24.7 percent) was approximately one half that of containerized stock and one third that of potted stock. This pattern in survival was observed in both species as well (table 2). Potted seedlings exhibited greatest survival, followed by containerized seedlings, followed by bare-root seedlings with the lowest survival.

Table 1—Overall survival for planting stock types (all treatments)

Planting stock	Survival
	-- *percent* --
Containerized	50.2b[a]
Potted	82.0a
Bare-root	24.7c

[a]values within a column followed by different letters are significantly different at $\alpha = 0.05$ (Duncan's Multiple Range Test).

Table 2—Overall survival for Nuttall oak and cherrybark oak by planting stock type (all treatments)

Planting stock	Nuttall oak	Cherry-bark oak
	---------- *percent*	-----------
Containerized	53.3b[a]A[b]	47.0bA
Potted	95.3aA	68.7aB
Bare-root	36.6cA	12.7cB

[a]values followed by different lower case letters within a column are significantly different at $\alpha = 0.05$ (Duncan's Multiple Range Test).
[b]values followed by different upper case letters within a row are significantly different at $\alpha = 0.05$ (Duncan's Multiple Range Test).

On a species basis, Nuttall oak exhibited greater overall survival than cherrybark oak (61.7 percent and 42.8 percent, respectively). Greater survival of Nuttall oak was also observed for comparable planting stock types in cherrybark oak (table 2). Early growing season saturated soil conditions are thought to have influenced the low survival observed for cherrybark oak. Subsequently, summer drought conditions are thought to also have contributed to much of the mortality observed across all species/planting stock combinations.

Survival/Site Preparation

Chemical site preparation worked well in controlling existing vegetation at the time of application. However, chemical site preparation did not control growing season herbaceous competition, nor was it expected to. The lowest survival was observed in areas receiving the Subsoil Only and Subsoil/OneStep® treatment combinations (47.2 percent and 41.1 percent, respectively) (table 3). Subsoil/Chopper EC® and Subsoil/Arsenal AC® treatment areas exhibited 57.7 percent and 50.9 percent survival. The discrepancy between areas that received a chemical application as a part of site preparation was likely the result of site condition differences and not the herbicide treatment. Areas on which the Subsoil/OneStep® treatment was applied were at the lowest elevations. These areas were inundated during much of the early growing season and remained saturated through June. The greatest overall survival (68.8 percent) was observed in Subsoil Only treatment areas. Lower survival in areas receiving a chemical component to site preparation was thought to be a result of recolonization of an aggressive broadleaf weed complex.

SUMMARY

Greater survival was observed for Nuttall oak than for cherrybark oak both on a species basis and on an individual planting stock basis. The much lower overall survival exhibited by cherrybark oak indicates that the species was probably not suited for saturated soil conditions found onsite during the early part of the growing season. Nuttall oak is considered more water tolerant than cherrybark oak (Burns and Honkala 1990, Day III and others 1997, Miwa and others 1992, Williams and others 1992). Findings of these

Table 3—Overall survival by site preparation treatment (all planting stocks)

Site preparation	Survival
	----- *percent* -----
Control	47.2c[a]
Subsoil Only	68.8a
Subsoil/Chopper EC®	57.7b
Subsoil/Arsenal AC®	50.9b
Subsoil/OneStep®	41.1c

[a]values within a column followed by different letters are significantly different at $\alpha = 0.05$ (Duncan's Multiple Range Test).

studies seem to be supported by the fact that cherrybark oak survived best on drier portions of the research site in this study.

Generally, greater survival is expected in potted stock, followed by containerized and bare-root planting stocks (Allen and others 2001, Burkett 1996, Howell 2002, Rathfon and others 1995, Williams and Craft 1997). As expected, potted stock exhibited the greatest survival, containerized second greatest, and bare-root stock exhibited the worst survival in this study. Bare-root survival can be excellent, but competition has to be controlled and uncontrollable natural site conditions have to be conducive to the desired outcome.

An interesting result was that the greatest overall survival observed (68.8 percent) was in areas receiving only subsoiling as a site preparation treatment. Survival in these areas was significantly greater than in areas receiving an additional chemical component to the site preparation treatment combination. This indicates if adequate competition control is not achieved with chemical site preparation, greater survival can be achieved through the use of subsoiling only. In this case aggressive broadleaf competition, which invaded areas "cleared" by the chemical site preparation, encroached at levels sufficient to negatively impact seedling survival. Subsoil Only treatment areas did not experience the increased broadleaf competition levels that other site preparation treatment areas did, resulting in significantly greater survival.

Subsoiling probably alleviated preexisting site condition problems as well. Earlier studies substantiate that seedlings benefit from subsoiling in former agricultural fields (Allen and others 2001, Ezell and Shankle 2004, Johnson and others 2002, Lockhart and others 2003). The biggest concern in regenerating retired agricultural fields is that of compacted soils (Allen and others 2001). Subsoiling fractures restrictive layers found in retired fields and can increase survival of planted seedlings. Subsoiling can also result in greater survival from increased nutrient and water uptake, deep root development, and higher levels of soil exploitation by developing root systems. These benefits are probably responsible for some of the survival observed in Subsoil Only areas.

It should be noted that the chemical site preparation treatments used in this study can provide excellent short term control of competing vegetation. Chemical site preparation should be used only to control species which cannot be eliminated by growing season herbaceous weed control efforts. It is these herbaceous release applications that typically provide longer term control of competition if the proper herbicide is used. Chemical site preparation is of little value if it does not control vegetation throughout the growing season. Thus, when chemical control is deemed necessary to control existing onsite vegetation, it should be followed by growing season herbaceous control. This is evidenced through survival observed in Subsoil Only areas. Greater overall survival would generally be expected in areas receiving both mechanical and chemical site preparation, but areas receiving the Subsoil Only treatment exhibited significantly greater survival. Areas treated with chemical site preparation did not receive growing season competition control and subsequently, survival in these areas suffered.

CONCLUSION

Generally, best survival results would be expected in areas receiving both subsoiling and effective competition control. However, if an aggressive broadleaf competitor exists onsite and growing season herbaceous control is not an option, the best option might be to not perform any chemical applications. If adequate growing season control cannot be achieved, subsoiling can provide improved results when planting hardwoods on retired agricultural areas. Subsoiling is also beneficial as a site preparation treatment in its own right, with a proven track record in influencing increased survival.

Bare-root and containerized stock survival was considered unacceptably low in this study. Potted seedlings survived the best, but the cost of using such seedlings ($1,216.00 per acre) would be prohibitive in most afforestation efforts. Containerized seedlings exhibited survival approximately one-half that of potted seedlings, but much greater than bare-root seedlings. In this case, containerized seedlings were less expensive than bare-root or potted seedlings due to bare-root and potted seedling size and associated planting costs. Containerized stock could be planted at higher densities to achieve survival equal to or exceeding potted stock survival at a fraction of the cost.

Hardwood plantings are never guaranteed, but greater survival should be expected than observed in this study. As land managers we can control species selection, seedling and planting quality, pre-plant seedling treatments, site preparation treatments, and post-plant herbicide treatments in the attempt to establish successful hardwood plantings. Natural factors such as droughty conditions or flooding cannot be prevented. The only thing we can do to counter effects of adverse natural conditions and increase the chance of planting success is to make the best silvicultural choices possible to promote planting survival.

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EVALUATING THE USE OF ENHANCED OAK SEEDLINGS FOR INCREASED SURVIVAL AND GROWTH: FIRST-YEAR SURVIVAL

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Abstract—Oaks (*Quercus* spp.) are very important in the southern landscape for timber production and wildlife habitat. More landowners are attempting to establish oak plantations as the demand for wood products and wildlife habitat continues to increase. These attempts are not always successful with early growth and survival becoming major concerns. In this study, 6,480 1-0 bareroot Nuttall oak (*Quercus nuttallii* Palmer) and white oak (*Quercus alba* L.) seedlings were planted in February 2005 on the Malmaison and Copiah County Wildlife Management Areas (WMAs) in MA. Half of the seedlings are high quality nursery-run seedlings and the other half are "enhanced" seedlings grown under a special nursery protocol developed by Dr. Paul Kormanik. The impact of various planting method, competition control, and fertilization treatments on seedling survival was evaluated during the first year following planting. First year survival did not differ significantly among nursery stocks. Seedling survival differed significantly among competition control and planting method treatments at Malmaison WMA.

INTRODUCTION

Oaks (*Quercus* spp.) are a very important component of the southern landscape for timber production as well as wildlife habitat. Thousands of acres are artificially regenerated with oak seedlings annually. As of 2002, more than 300,000 acres of retired agricultural land have been afforested in the Lower Mississippi Alluvial Valley (LMAV) (Ezell and Shankle 2004). By 2040, it is estimated that more than 30 million acres of retired agricultural land across the South will be planted in trees, with millions of these acres being planted in hardwoods (Wear and Greis 2002). This is largely due to increasing landowner participation in federal cost-share programs and interest in improving wildlife habitat (Ezell and Nelson 2001).

More landowners are attempting to establish oak plantations as demand for wood products and wildlife habitat continues to increase. However, artificial regeneration attempts are not always successful, and early growth and survival have become major concerns as newly planted oak seedlings are often subjected to harsh site conditions including herbaceous competition, herbivory, drought, and flooding (Schweitzer and others 1999). Also, landowners with wildlife interests are concerned about the length of time required for an oak tree to produce acorns. Benefits would be tremendous if oak establishment could be facilitated and the length of time required to produce acorns shortened.

Few forest tree nurseries were growing hardwoods in the Southern United States before the mid 1980s because the primary emphasis was on pine seedling production. This began to change as groups such as furniture manufacturers and wildlife organizations became concerned about the decline of oak forests in the Southern United States. Oak seedlings being grown in nurseries often were of poor quality. In 1984, the USDA Forest Service Institute of Tree Root Biology (ITRB) in Athens, GA initiated research to develop a nursery protocol for growing oak seedlings that would enable the formulation of a biologically based grading system (Kormanik and others 2003). The major ITRB goal was to develop a reliable nursery protocol to consistently produce seedlings of sufficient size for advance oak regeneration in cleared areas. This protocol has proven successful in producing quality oak seedlings from 10 oak species and many other hardwood species (Kormanik and others 2002a).

Studies have shown that using "enhanced" oak seedlings (seedlings produced under the special nursery protocol) in conjunction with intensive establishment procedures can improve early growth and survival, and reduce the length of time required for an oak tree to produce acorns (Kormanik and others 2002b). However, the relative importance of seedling parameters, site preparation methods, planting methods, competition control, and fertilization in this process is currently unknown. Very few studies have compared the initial performance of "enhanced" seedlings to nursery-run seedlings. Also, more information is needed on the effects that these practices have on establishing oak plantings and facilitating growth and development.

OBJECTIVES

The objectives of this study were:

1. To evaluate survival and initial growth response of oak seedlings produced under special nursery protocols ("enhanced" seedlings) compared to nursery-run oak seedlings of the same species.
2. To evaluate influence of various cultural practices including competition control, planting method, and fertilization on initial seedling performance of these same nursery stocks.

MATERIALS AND METHODS

Site Description

This study was conducted on Malmaison WMA and Copiah County WMA. Malmaison WMA is located in Grenada County approximately 14 miles north of Greenwood, MS. Copiah County WMA is located in Copiah County approximately 16 miles west of Hazlehurst, MS. Each study area encompasses approximately 7.5 acres of retired agricultural land. Soils within

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research plots on Malmaison WMA consisted of silt loam with a pH ranging from 6.1 to 7.4. Copiah County WMA research plots consisted of silt soils with a pH ranging from 5.2 to 5.8.

Seedlings

Nuttall oak (*Quercus nuttallii* Palmer) and white oak (*Quercus alba* L.) seedlings were chosen for this study because they are two of the most commonly planted species in the South. At each study site, 3,240 1-0 bare-root seedlings were planted at a spacing of 10 by 10 feet in February 2005. Half of seedlings planted are nursery-run seedlings of good quality from the Molpus Timberlands Nursery near Elberta, AL. The other half of seedlings ("enhanced" seedlings) were grown at the Flint River Nursery near Byromville, GA. Enhanced seedlings are very high-quality seedlings that are capable of acorn production at early ages and growing exceptionally well when managed intensively (Kormanik and others 2002a, Kormanik and others 2003). The management regime that has resulted in this growth/acorn production included planting in augered holes, fertilization, and complete competition control for each growing season after planting.

Treatments

Planting method—Three planting methods were utilized in this study. These methods included hand planting with shovels in subsoiled trenches, augering, and hand planting with planting shovels with no soil treatment ("flat" planting). Subsoiling was done with a tractor to a depth of approximately 18 inches. A tractor-mounted, eight-inch auger was used for augering. If necessary, augered holes were backfilled prior to planting so that seedling root collars were placed close to or slightly above ground level.

Fertilization—Half of seedlings received fertilization at planting. A 30-gram packet of 22-10-7 NPK fertilizer designed specifically for hardwood seedlings was used for each seedling to be fertilized. The fertilizer packet was placed in a separate slit approximately one inch from the planted seedling for the hand planting only and subsoiling methods. For auger planted seedlings, the fertilizer packet was placed at the bottom of the augered hole and covered with soil to keep from having direct contact with seedling roots.

Competition control—Three competition control treatments were used in this study. These treatments included pre-emergent application only, control for one full growing season, and total competition control (all years). The pre-emergent application only treatment consisted of one application of Oust XP® applied over the top of seedlings at a rate of two ounces per sprayed acre in March 2005. The one growing season and total competition control treatments were the same for the first growing season. These treatments also included a pre-emergent application of Oust XP® in March 2005. Additionally, these treatments included an application of Select® or Clethodim 2EC® at a rate of 16 ounces per sprayed acre in June 2005 to help control bermudagrass (*Cynodon dactylon* (L.) Pers.) not controlled by the previous application of Oust XP®. Finally, the one growing season and total competition control treatments also consisted of directed applications of glyphosate (1.5 percent v/v) as needed from June to November 2005 for control of forbs and other plants not controlled by the earlier applications.

Experimental Design

A three-split strip-plot in a randomized complete block design with sub-sampling was used in this experiment. Each study site consists of three replications. Each replication contains one of each possible species/nursery stock/planting method/fertilization/competition control combination. Each replication consists of 72 plots that are approximately 150 by 10 feet. Each plot contains 15 seedlings.

Seedling Evaluation

Seedling survival was recorded monthly during the 2005 growing season with an exception of September due to complications from Hurricane Katrina. Seedling survival was based on ocular evaluation. All missing seedlings were considered dead. If a seedling was observed as a resprout in later observations, it was reinstated in earlier survival estimations. The cambium was checked on seedlings which appeared dead to ensure survival status.

Statistical Analysis

Analyses were performed using a mixed procedure in Statistical Analysis System (SAS) software version 9.1®. Analyses were separated by species and site. Survival data for both species at each site were analyzed for interactions among nursery stock, planting method, fertilization, and competition control treatments. A mixed model analyses of variance (ANOVA) was used to test for main effects and interactions. Data were analyzed using least square means (LSMEANS). Survival percentages were arcsine square root transformed to normalize the data. However, actual means are presented for ease of data interpretation. Means were considered significant if $P < 0.05$.

RESULTS AND DISCUSSION

Nuttall oak seedlings exhibited excellent survival at Copiah County WMA during the first growing season. Survival did not differ significantly among treatments. Survival of enhanced and nursery-run Nuttall oak seedlings in October was 99.96 percent and 99.98 percent, respectively (table 1). White oak seedling survival was also excellent during the first growing season at Copiah County WMA. Again, there were not any significant survival differences among treatments. Survival of enhanced and nursery-run white oak seedlings in October was 99.24 percent and 98.62 percent, respectively (table 2). Planting method, fertilization, and competition control treatments had no significant effect on survival. This excellent survival probably resulted from controlling competing vegetation, using high- quality seedlings, and proper handling and planting of these seedlings. This is similar to other studies which have attributed excellent first year survival to quality seedlings, quality handling and planting, and proper species selection for the study site (Schweitzer and others 1999, Gardiner and others 2002, Heitzman and Grell 2003).

Nuttall oak seedlings also exhibited excellent survival during the first growing season at Malmaison WMA. Significant differences in Nuttall oak survival did occur among competition control treatments and among planting method/competition control combinations. Survival of enhanced and nursery-run Nuttall oak seedlings in October was 97.85 and 97.42 percent, respectively (table 3). Nuttall oak seedlings

Table 1—Average Nuttall oak seedling survival during the first growing season, June - October 2005, at Copiah County WMA (includes all treatments)

	Timing of Observation			
Nursery stock	June	July	August	October
	Percent			
E[a]	100.00a[b]	99.98a	99.96a	99.96a
NR	100.00a	99.98a	99.98a	99.98a

[a]E = enhanced, NR = nursery-run.
[b]Values within a column with the same letter do not differ at $\alpha = 0.05$.

Table 2—Average white oak seedling survival during the first growing season, June - October 2005, at Copiah County WMA (includes all treatments)

	Timing of Observation			
Nursery Stock	June	July	August	October
	Percent			
E[a]	100.00a[b]	99.93a	99.57a	99.24a
NR	99.99a	99.44a	98.74a	98.62a

[a]E = enhanced, NR = nursery-run.
[b]Values within a column with the same letter do not differ at $\alpha = 0.05$.

receiving total competition control had significantly greater survival than seedlings receiving pre-emergent only or first growing season treatments (table 4). Survival of seedlings receiving total competition control, pre-emergent only, and first growing season treatments was 99.06, 96.75, and 96.12 percent, respectively. Even though these differences were statistically significant, they were not biologically significant as survival for Nuttall oak was greater than 96 percent in all competition control treatments. Also, the one growing season and total competition control treatments were the same for the first growing season. Therefore, survival differences occurring between these two treatments could have been the result of individual seedlings coming in contact with drifting spray of glyphosate solution. Some mortality was noticed early in the growing season. It is possible that other factors such as improper handling or planting of individual seedlings resulted in these minor differences in Nuttall oak seedling survival.

Survival of Nuttall oak seedlings at Malmaison WMA was greater than 90 percent for all planting method/competition control combinations except the pre-emergent only/hand planting combination (87.58 percent) (table 5). Subsoil and auger planted Nuttall oak seedlings receiving pre-emergent only competition control had survival 11.24 to 11.86 percent greater than survival of hand planted seedlings receiving pre-emergent only competition control. These results indicate that the hand planted seedlings did not tolerate the competition as well as the subsoil and auger planted seedlings. Subsoil and auger planted seedlings were likely able to gain better root establishment before the onset of heavy competition. Subsoiling increases the amount of soil exploited by seedling roots, improves aeration, and can increase soil moisture availability (Russell and others 1997, Gardiner and others 2002). Other studies have shown that subsoiling improved first year oak seedling survival (Johns and others 1999, Self 2006).

Table 3—Average Nuttall oak seedling survival during the first growing season, June - October 2005, at Malmaison WMA (includes all treatments)

	Timing of Observation			
Nursery Stock	June	July	August	October
	Percent			
E[a]	99.68a[b]	99.50a	98.09a	97.85a
NR	99.49a	99.25a	97.93a	97.42a

[a]E = enhanced, NR = nursery-run.
[b]Values within a column with the same letter do not differ at $\alpha = 0.05$.

Table 4—Average seedling survival in different competition control treatments after one growing season at Malmaison WMA (includes all nursery stock, planting method, and fertilization treatments)

Competition Control	Nuttall Oak	White Oak
	Percent	
PEO[a]	96.75b[b]	79.72a
1GS	96.12b	77.97a
T	99.06a	71.13b

[a]PEO = pre-emergent only, 1GS = first growing season, T = total (all years)
[b]Values within a column with the same letter do not differ at $\alpha = 0.05$.

Table 5—Average Nuttall oak seedling survival after one growing season in different planting method/competition control combinations at Malmaison WMA (includes all nursery stock and fertilization treatments)

	Competition Control		
Planting Method	PEO[b]	1GS	T
	Percent		
H[a]	87.58b[c]B[d]	96.44aA	98.61aA
S	98.82aAB	94.94aB	99.04aA
A	99.44aA	96.84aA	99.44aA

[a]H = hand, S = subsoil, A = auger
[b]PEO = pre-emergent only, 1GS = first growing season, T = total (all years)
[c]Values within a column with the same lower case letter do not differ at $\alpha = 0.05$.
[d]Values within a row with the same upper case letter do not differ at $\alpha = 0.05$.

First growing season white oak seedling survival at Malmaison WMA was the lowest among all seedlings. Significant differences in white oak survival did occur among competition control treatments. Survival of enhanced and nursery-run white oak seedlings in October was 76 and 76.74 percent, respectively (table 6). Survival remained above 90 percent until after July observations. In August, survival had dropped to 78.92 and 79.21 percent for enhanced and nursery-run seedlings, respectively. Survival of white oak seedlings receiving total competition control was significantly lower than survival of seedlings receiving pre-emergent only or one growing season treatments (table 4). Survival of white oak seedlings receiving total competition control, pre-emergent only, and one growing season treatments was 71.13, 79.72, and 77.97 percent, respectively.

White oak seedlings suffered greater than 20 percent mortality, regardless of which competition control treatment was applied (table 4). Additional mortality occurred with seedlings receiving one growing season or total competition control treatments. As mentioned earlier, the one growing season and total competition control treatments were the same for the first growing season. Again, survival differences occurring between these two treatments could have been the result of individual seedlings coming in contact with drifting spray of glyphosate solution. Also, variations in the intensity of herbaceous competition could have resulted in white oak seedling survival differences across these treatments.

The drop in white oak seedling survival between July and August observations was probably the result of a rapid increase in competition early in the growing season combined with droughty conditions. White oak seedlings were much smaller than Nuttall oak seedlings, and many were overtopped by herbaceous competition before competition could be treated. It is also very likely that drifting spray of glyphosate solution contacted some seedlings, especially those that were overtopped by competing vegetation. This could have also resulted in seedling mortality. However, survival of seedlings in plots not receiving glyphosate treatment was almost as low, indicating that herbicide drift was not the only cause of seedling mortality. Other studies have reported seedling mortality resulting from herbicide drift (Buckley 2002, Krekeler and others 2006).

Table 6—Average white oak seedling survival during the first growing season, June - October 2005, at Malmaison WMA (includes all treatments)

	Timing of Observation			
Nursery Stock	June	July	August	October
	Percent			
E[a]	97.84a[b]	92.95a	78.92a	76.00a
NR	98.66a	92.49a	79.21a	76.74a

[a]E = enhanced, NR = nursery-run.
[b]Values within a column with the same letter do not differ at $\alpha = 0.05$.

CONCLUSION

Enhanced and nursery-run seedling survival did not differ significantly. The smaller nursery-run seedlings were just as competitive as enhanced seedlings. Seedling survival did not differ significantly between fertilized and non-fertilized seedlings. There were no significant treatment effects on seedling survival at Copiah County WMA, as all seedlings exhibited greater than 98 percent survival after one growing season. In most cases, survival did not differ significantly among planting methods. However, when survival did differ significantly among planting methods, it was with seedlings receiving pre-emergent only competition control. Survival of hand planted seedlings receiving pre-emergent only competition control was significantly lower than survival of subsoil and auger planted seedlings receiving pre-emergent only competition control. The effect of competition control on seedling survival was different by species. Nuttall oak survival was greatest with seedlings receiving total competition control, while white oak survival was greatest with seedlings receiving pre-emergent only competition control. However, differences in Nuttall oak seedling survival among competition control treatments were not biologically significant. Additional white oak seedling mortality occurred at Malmaison WMA in plots receiving glyphosate treatment. Increased mortality resulted from herbicide spray drift contacting some of the white oak seedlings.

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DETERMINING THE FACTORS ASSOCIATED WITH SEEDLING HERBIVORY ON AFFORESTED CARBON SEQUESTRATION SITES IN THE LOWER MISSISSIPPI ALLUVIAL VALLEY: PRELIMINARY RESULTS

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Abstract—One causal factor of failed afforestation attempts in the Lower Mississippi Alluvial Valley (LMAV) is mammalian herbivory. Herbivory of seedlings generally reduces growth and can also lead to seedling mortality. Seedlings were randomly selected for monitoring throughout the first growing season. Growth and survival data were recorded, as were signs of mammalian herbivory. Analysis of variance (ANOVA) was conducted and it was determined that species mix and the application of slow-release fertilizer tablets had a significant effect on seedling survival rates and overall seedling herbivory rates after one growing season. Future research will provide additional input as to what factors are most responsible for determining seedling survival and anticipated seedling herbivory in afforested areas in the LMAV. Based on the results of this study, we hope to identify a cost-effective species mix that can be utilized in the LMAV to promote carbon sequestration and withstand the negative impacts of potential browsing by mammalian herbivores.

INTRODUCTION

There is rising global concern in light of possible negative consequences of climatic change due to increasing atmospheric levels of carbon dioxide. A contributing factor responsible for rising levels of atmospheric carbon dioxide is the decreasing amount of forest land in the world (Mickler 2004). The Lower Mississippi Alluvial Valley (LMAV) has experienced widespread loss of bottomland hardwood forests and forested wetlands as lands in this region have been cleared for agricultural use over the past two centuries (Stanturf and others 2000). However, it is projected that nearly 34 million acres of retired agricultural land in the LMAV will be available for hardwood plantings by 2040 (Wear and Greis 2002). These areas will provide landowners with opportunities for potential income through timber production, enhanced wildlife habitat, potential income from fee hunting, and the sale of credits associated with carbon sequestration.

While it has been suggested that production of forest products can be financially superior to agricultural production on marginal lands in the LMAV (Amacher and others 1998), it is important to note that these analyses assume afforestation success and full stocking of target species. Early afforestation efforts undertaken in the LMAV over the last several decades have been characterized by inconsistent crop tree survival, species composition, and site productivity (Stanturf and others 2004). Thus, it is important to consider what causes the failures and inconsistencies that have marred afforestation activities. Many factors are responsible for poor survival and growth of afforestation areas in the LMAV. These include mammalian herbivory, herbaceous plant competition, nutrient deficiency, poor site suitability, lack of site preparation, and low-quality planting stock (Stanturf and others 2004).

When establishing hardwood species in the LMAV, one problem that hinders seedling establishment is the occurrence of mammalian herbivory (Stanturf and others 1998). Herbivory of seedlings generally reduces growth; increases competitive disadvantage; and can also lead to seedling mortality (Buckley 2002). Herbivory in the LMAV can be attributed to mammalian species such as white-tail deer (*Odocoileus virginianus*), rabbits (*Sylvilagus* spp.), and various rodent species such as hispid cotton rats (*Sigmodon hispidus*) and wood rats (*Neotoma floridanus*) (Stange and Shea 1998). In a bottomland hardwood planting, herbivory can cause regeneration delays (Stanturf and others 1998). These delays can have significant economic impacts on landowners who are interested in planting bottomland hardwoods in the LMAV (Straka and Hotvedt 1985).

Little empirical research has been conducted examining which environmental factors influence the occurrence and likelihood of wildlife herbivory on afforested areas in the LMAV. Jones and others (1997) reported that herbivores show selective preference toward specific browse species. Additionally, numerous studies have indicated that various red and white oak species are favored by herbivores (Cadenasso and Pickett 2000, Lockhart and others 2000, Taylor and others 2006, Oswalt and others 2006).

It has been suggested that perhaps the most feasible means of herbivory control is proper site preparation activities (Stanturf and others 2004). Small mammals such as rodents, voles, and rabbits prefer a densely vegetated ground layer that provides escape cover from aerial and terrestrial predation (Ostfeld and others 1997, Schnurr and others 2004). Thus, the removal of neighboring herbaceous competition through mechanical or chemical means has been suggested as a tactic that will limit or reduce small mammal habitat in afforested settings. However, it has been documented that open seedlings are more vulnerable to

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predation by white-tail deer (Buckley and others 1998, Dubois and others 2000, Castleberry and others 2000, Sweeney and others 2002). However, Stange and Shea (1998) suggest that small mammal herbivory is often more detrimental to seedlings than deer browsing.

STUDY SITE AND METHODS

In February 2006, seedlings were planted at Entergy Company's Delta steam electric generating station located approximately 2 miles north of Cleveland, MS as part of a larger carbon sequestration project that was undertaken by Entergy and Mississippi State University. Hardwood seedlings were hand-planted at a spacing of 10 by 10 feet, resulting in approximately 435 trees per acre. Plots were established as a 6 by 2 by 2 completely randomized factorial design using six species mixes by two fertilizer treatments (fertilized vs. non-fertilized) by two competition treatments (chemical vs. no chemical control). Fifty percent of all seedlings were treated with a 15:10:20 slow release fertilizer tablet following planting. Additionally, 50 percent of all seedlings received chemical competition control in the form of a post-emergent application of Goal 2XL at a rate of 64 ounces per acre in May 2006. Herbicide treated seedlings also received an additional treatment of Goal 2XL at a rate of 32 ounces per acre in August 2006. Thus, 25 percent of seedlings from each species mix received the following treatments: fertilizer only, herbicide only, fertilizer and herbicide combination, or neither fertilizer nor herbicide (control).

Three replications of each of the 24 treatment combinations (afforestation regimes) were established, resulting in 72 0.25-acre plots at both study sites. Seedlings from each afforestation regime were randomly selected for monitoring throughout the first growing season. Selected seedlings were marked using aluminum tree tags and 3-foot pin flags to compensate for dense herbaceous vegetation. Selected seedlings were visited three times during the 2006 growing season (March, July, and October) and once more in February 2007. Seedling herbivory, when evident, was recorded and the herbivore species responsible for that damage was determined using browsing characteristics described by Jackson (1990).

Analysis of variance (ANOVA) was used to identify treatment effects and factor-level interactions that existed in survival, growth, and herbivory data. Statistical analysis was conducted using the mixed procedure in SAS 9.1. All statistical analysis was done at the 95 percent confidence level.

RESULTS

The results discussed in this publication refer to data recorded between February 2006 and February 2007 at Entergy's carbon sequestration site in Cleveland, MS. The three species mixes analyzed are composed of the following seedling species: Mix A- eastern cottonwood (*Populus deltoides*) monoculture, Mix B–red mulberry (*Morus rubra*) monoculture, and Mix C–50 percent eastern cottonwood and 50 percent mix of willow oak (*Quercus phellos*), Nuttall oak (*Quercus nuttallii*), and water oak (*Quercus nigra*).

Survival

Overall seedling survival during the 2006 growing season was poor, as approximately 31 percent of selected seedlings remained after one growing season. Seedling species was determined to have a significant effect on seedling survival ($p = <0.0001$). Eastern cottonwood seedlings performed exceedingly poorly, as merely one percent of selected seedlings survived until October 2006, regardless of herbicide/fertilizer treatment (table 1). Thus, Species Mix A and Species Mix C exhibited survival rates that were significantly lower than the survival rates exhibited by all other species mixes. Species Mix B, the red mulberry monoculture, expressed survival rates that were among the highest observed, as approximately 60 percent of selected red mulberry seedlings survived. Oak seedlings in Mix C survived at a rate of approximately 20 percent during the first growing season.

It was also determined that the application of slow-release fertilization tablets had a significant effect ($p = 0.0218$) on seedling survival rates. Seedlings receiving a first year fertilizer application were less likely to survive than seedlings receiving no fertilization (table 2). The application of post-emergent herbicide was determined to have no significant effect ($p = 0.9347$) on seedling survival at the Cleveland, MS carbon sequestration site.

Herbivory

Herbivory occurred on a substantial number of seedlings the year following afforestation. Approximately 22 percent of selected seedlings were browsed by a mammalian herbivore. More than 60 percent of observed mammalian herbivory was attributed to hispid cotton rats while rabbits accounted for nearly 25 percent of seedling herbivory. Pine voles were only responsible for browsing approximately 15 percent of observed seedling herbivory. Herbivore damage ranged from severance of the root system to clipping of minor branches and twigs.

Seedling species was determined to have a significant effect ($p = < 0.0001$) on the likelihood of seedling herbivory (table 1). Eastern cottonwood browsing was rare, as less than

Table 1—First-year seedling survival and herbivory rates by planting mix observed at the Cleveland, MS site of the Entergy Afforestation Project during the 2006 growing season. Data were analyzed at the 95 percent confidence level

Species Mix	% Survival[a]	% Herbivory[a]
A- Eastern cotton-wood monoculture	1.0c	0.0c
B- Red mulberry monoculture	66.4a	33.9a
C- Eastern cotton-wood/oak mix	5.7b	16.3b

[a]Values followed by the same letter do not differ statistically at $\alpha = 0.05$.

Table 2—First-year seedlings survival and herbivory rates by fertilization and herbicide application observed at the Cleveland, MS site of the Entergy Afforestation Project during the 2006 growing season. Data were analyzed at the 95 percent confidence level

Treatment	% Survival[a]	% Herbivory[a]
Fertilization		
Yes	26.1b	17.3b
No	34.8a	25.6a
Herbicide		
Yes	29.2a	22.6a
No	31.6a	21.0a

[a]Values followed by the same letter do not differ statistically at $\alpha = 0.05$.

one percent of selected seedlings in Mix A exhibited signs of mammalian browsing. More than 30 percent of selected red mulberry seedlings from Mix B exhibited browsing from an herbivore. Oak seedlings were typically browsed more readily than any other species, as up to half of selected oak seedlings were browsed in some afforestation regimes. Mix C, the eastern cottonwood/oak mix was browsed at a rate of approximately 16 percent during the 2006 growing season.

It was determined that fertilization had a significant effect ($p = 0.0233$) on expected mammalian herbivory rates (table 2). Seedlings receiving fertilization were less likely to be browsed than seedlings not fertilized. Post-emergent herbicide application was determined to have no significant effect on seedling herbivory.

DISCUSSION

Overall seedling survival during the 2006 growing season was low. Poor seedling survival can likely be attributed to the combined effects of intense herbaceous competition, wildlife herbivory, and drought conditions during the early part of the growing season. The use of Goal 2XL for chemical competition control was dictated by the inclusion of eastern cottonwood into this project, because more aggressive herbicides such as Oust XP are not available for use on eastern cottonwood seedlings. The selected herbicide application had little effect on competition from herbaceous species such as tall fescue (*Festuca arundinacea*), verbena (*Verbena brasiliensis),* peppervine (*Ampelopsis arborea*), and blackberry (*Rubus argutus*). Thus, the use of this particular herbicide regime had no significant effect on seedling survival although effective first year competition control can tremendously improve hardwood seedling growth and survival (Ezell 1994, Ezell and others 2007).

As expected, species mix was a significant factor effecting seedling survival. Mix A, the eastern cottonwood monoculture, performed very poorly. These results were expected as eastern cottonwood seedlings are poor competitors and successful establishment typically requires complete competition control during the first growing season (Ezell 1994). Species Mix B, the red mulberry monoculture, exhibited survival rates in excess of 60 percent for each treatment combination. However, surviving red mulberry seedlings were typically characterized by die-back and displayed minimal first year height growth. Monitored oak seedlings survived at a rate of approximately 40 percent during the first growing season for all treatment combinations. These poor survival rates are characteristic to the results of many afforestation efforts in the past, yet could be improved with proper site preparation, chemical competition control, and increased rainfall.

Fertilization significantly decreased survival rates for seedlings in each seedling mix examined. Due to the dense herbaceous layer at this site, it is likely that seedlings were not able to utilize the added nutrients provided by fertilization. Furthermore, it is likely that competing herbaceous vegetation was able to utilize the nutrients provided by fertilization much more efficiently than first year hardwood seedlings, thus compounding competitive disadvantage (Hopper and others 1993). Due to the apparent lack of efficacy provided by herbicide application, it was determined that the selected chemical competition control had no effect on seedling survival rates.

Small mammal herbivores such as hispid cotton rats, rabbits, and pine voles were responsible for browsing over 20 percent of selected seedlings during the year following planting. The dense herbaceous layer characterizing this site likely created suitable escape cover and feeding habitat for these herbivores, thus subjecting seedlings to substantial browsing pressure. Effective chemical competition control likely would have decreased small mammal abundance and herbivory, increasing seedling growth and survival rates (Stanturf and others 2004).

Seedling species was identified as a significant factor determining seedling herbivory rates. Eastern cottonwood seedlings were rarely browsed, most likely due to poor survival rates exhibited by eastern cottonwood seedlings. However, few studies have indicated that herbivory is a major problem in eastern cottonwood plantings. During the 2006 growing season, red mulberry and oak seedlings were browsed much more readily than eastern cottonwood seedlings. The seemingly increased vulnerability of these species is supported by previous research (Cadenasso and Pickett 2000, Lockhart and others 2000, Oswalt and others 2006, Taylor and others 2006).

Fertilized seedlings were less likely to be browsed than seedlings receiving no fertilization. Since fertilized seedlings were less likely to survive, it can be inferred that fewer fertilized seedlings were available to be browsed upon. Research conducted by Taylor and others (2006) reported that fertilization of Nuttall oak seedlings had no effect on observed herbivory rates. Herbicide application had no effect on seedling herbivory rates for any species mix. Due to the inefficacy of the selected herbicide regime at controlling competing vegetation, differences among seedlings were not expected.

CONCLUSIONS

The occurrence of wildlife herbivory during the early stages of afforestation attempts is an area of concern to landowners in the LMAV. The early results of this study indicate that mammalian herbivory can occur over a wide range of seedling species and silvicultural activities. The results are important because substantial browsing by various herbivore species can impact seedling vigor, growth, and survival. In extreme cases, the additional stress caused by wildlife herbivory can lead to afforestation delay or stand establishment failure.

It is currently uncertain to what extent mammalian herbivory impacts survival, growth, and carbon sequestration in young bottomland hardwood forests. It is also unknown what monetary implications herbivory may have for landowners and natural resource professionals who invest in planting hardwood seedlings in the LMAV. Since recent trends and predictions suggest that afforestation efforts in the LMAV will continue to expand over the next several decades, it is important to assess the impact of mammalian herbivory in this area. Increased understanding of the ecological interactions that take place on afforested sites will allow land managers to better implement silvicultural activities that best promote successful seedling establishment.

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GROWING COTTONWOODS FOR BIOMASS: RESULTS OF A TEN-YEAR IRRIGATION STUDY

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Abstract—Eastern cottonwood (*Populus deltoides* Bartr.) has potential as a short rotation alternate crop on marginal farmlands in the South to meet increasing biomass demands for pulp and bioenergy applications. Potlatch Corporation supported this study to investigate the effect of irrigation on the growth of cottonwood trees. The study was installed in the Delta region of AR in 1996. Survival, height, diameter, and biomass production of the various cottonwood clones were compared between the irrigated-bedded treatment and the unirrigated-subsoiled treatment. Several clones were replanted the second year due to poor initial survival. Data are presented for replanted and non-replanted clones. Survival for some clones dropped off greatly after five years. Irrigation with bedding increased volume growth over no irrigation with subsoiling. Growth differences were also apparent among clones within each of the two irrigation treatments. Lower survival sometimes resulted in greater volume growth of the remaining trees. Overall, irrigation increased height, diameter, and volume growth of all clones.

INTRODUCTION

Eastern cottonwood (*Populus deltoides* Bartr.) is one of the fastest growing hardwood species in the United States. Many wood products are derived from cottonwood, including pulp for making high quality paper, furniture stock, crates and boxes, matches, and toothpicks (Dutrow and others 1970). Cottonwood trees grow best on well-drained sandy loam and silt loam soils near creek bottoms (McKnight 1970). The species has wide genetic diversity and can be easily propagated vegetatively by cuttings (Farmer and Wilcox 1964, Land and others 2001). These factors have made cottonwood a target of extensive research and selection for improved growth and disease resistance for more than 50 years (Land and others 1996). Selected and improved cottonwood clones are often grown as a short rotation woody crop to produce biomass for pulp. Interest has also increased in the South for converting the biomass to bioenergy. The performance of select clones usually varies by geographic origin and is influenced by other sources of genetic variation (Land and others 1996). Planting clones adapted to a given area, along with applying appropriate cultural treatments, can significantly improve biomass production.

This 10-year study was implemented by Potlatch Corporation and the University of Arkansas at Monticello School of Forest Resources. The purpose was to evaluate the response of selected cottonwood clones to irrigation. Irrigation could make growing cottonwood more viable on marginal lands.

METHODS

Site Location and Description

The study site is located at the University of Arkansas Pine Tree Branch Experiment Station in St. Francis County in east central AR. The study occupies about 15 acres near Second Creek. The soil is a Calloway silt loam. The site's previous use was a rotation of soybeans, wheat, and grain sorghum.

Study Design and Layout

The design is a split-plot, where the whole-plot is irrigation treatment, and the split-plot is clone of cottonwood. Each clone was replicated six times within each irrigation treatment in randomly assigned plots. Each plot contained 56 trees in a 7 by 8 tree layout. The interior 30 trees were measured, leaving an unmeasured buffer row around each measurement plot. The irrigated and unirrigated treatments were not randomized. Large buffers would have been required between the treatments, which were impractical for this study. Two treatment blocks were used, an unirrigated block and an irrigated block.

Study Establishment

The site was sprayed prior to planting with Goal® and Roundup® herbicides to control weeds. Fertilizer was applied before planting at the rate of 100 pounds per acre of nitrogen. The unirrigated block was subsoiled prior to planting, and the liquid fertilizer was injected 20 inches below the soil surface. In the irrigated block, each planting row was sprayed with the fertilizer in a 2-foot-wide band, and then bedded (20-inch-high beds) to facilitate furrow irrigation.

Cottonwood cuttings were planted by hand at a 10 by 10 foot spacing in March 1996. Disking, herbicide spraying, and hand weeding continued for two years after the initial planting. Irrigation with well water was done each year whenever a 2-inch-rainfall deficit was reached. This occurred an average of five times per year, resulting in about 8 to 10 acre-inches of irrigation water per year.

Nine cottonwood clones were tested, two from Texas (S7C15 and S13C20), five from Stoneville (ST72, ST124, ST148, ST163, and Delta View, a mix of the four ST clones), and two hybrids from the northwestern U.S. (*Populus trichocarpa* Torr. (49-177) and Gray x *P. deltoides* Bartr. ex Marsh [1529]).

Poor survival caused the complete replanting of five cottonwood clones (S7C15, ST72, ST148, ST163, and Delta View) in Spring 1997. This resulted in two separate groups of clones: replanted clones, which grew nine years, and non-replanted clones, which grew for 10 years. Measurement data for the two groups were then analyzed separately.

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Field measurements collected were survival and total height (years 1, 2, 3, 5, 10), groundline diameter (years 1, 2 for non-replants; also year 3 for replants), and d.b.h. (years 3, 5, 10 for non-replants; years 5, 10 only for replants).

Biomass produced by each tree (dry tons of total aboveground biomass per tree) was calculated according to the formula shown below (Jenkins and others 2003). Metric units in the formula were converted to English units.

$$\text{Biomass} = \text{Exp}(\beta0 + \beta1 \ln \text{d.b.h.}) \quad (1)$$

where

biomass = total aboveground biomass (kg) for trees 2.5 cm d.b.h. and larger

Exp = exponential function

ß0 = -2.2094 (for aspen/alder/cottonwood/willow species group)

ß1 = 2.3867 (for aspen/alder/cottonwood/willow species group)

ln = natural log base “e” (2.718282)

d.b.h. = diameter at breast height (cm)

RESULTS AND DISCUSSION

Irrigation Treatment

For the replanted clones, survival at year 10 across all clones was about the same for both irrigation treatments (table 1). However, growth and volume means were greater for the irrigated clones. For the non-replanted clones, survival was almost 20 percent higher for the irrigated clones (table 1). Irrigation also increased the other growth and volume means over the unirrigated clones. Irrigation of hybrid poplars, usually using drip systems, has been successful in increasing yields in the Northwestern United States. Irrigation in late summer may provide the most benefits (Land and others 1996).

Clonal Differences (Replanted Clones)

Survival trends for each of the replanted clones are shown in figure 1. Some clones had relatively consistent survival over the nine-year growth period, but survival rates for two clones (irrigated S7C15 and unirrigated ST72) dropped off considerably after age 4.

For the replanted clones, growth and volume means within each irrigation level are shown in table 2. For each parameter, means were higher for irrigated trees. Within the unirrigated treatment, clone S7C15 trees performed best in terms of per acre biomass production, while ST163 performed the best in the irrigated treatment (not significant).

Figure 2 compares percent volume growth for the replanted clones over the nine-year growth cycle by two periods: the first four and the second five years. For all five replanted clones, volume growth was greater the second five years, in some cases double or triple. Growing these clones through the second five-year period was definitely worthwhile.

Dutrow and others (1970) reported average diameters for 9-year-old unirrigated cottonwoods ranging from 6.5 inches on poor sites to 9.0 inches on good sites. Diameters for the unirrigated replanted clones in this study are much smaller.

Clonal Differences (Non-replanted Clones)

Survival trends for each of the non-replanted clones are shown in figure 3. Some clones had relatively consistent survival over the ten-year growth period, but survival rates for several clones dropped off considerably after age 5.

For the non-replanted clones, growth and volume means within each irrigation level are shown in table 3. For each parameter, means were higher for irrigated trees, except d.b.h. for clone 49-177. Within the unirrigated treatment level,

Table 1—Means for replanted and non-replanted clones, compared by irrigation treatment at year 10

Variable	Replanted clones		Non-replanted clones	
	Unirrigated	Irrigated	Unirrigated	Irrigated
Survival, %	61.2	59.2	38.6	57.8
Height, feet	30.5	50.7	34.7	52.7
Diameter, inches	4.53	6.66	6.08	7.68
Basal area, square feet per acre	32.3	66.3	36.2	78.5
Biomass per tree, dry tons	0.045	0.115	0.089	0.155
Biomass per acre, dry tons	12.4	29.3	15.4	35.8

Table 2—Height, diameter, basal area, and biomass per acre (volume) means for replanted clones by irrigation level. Within each irrigation level, clonal means followed by different letters are significantly different at α=0.05

Clone	Height, feet		DBH, inches		BA, square feet per acre		Biomass, tons per acre	
	unirr.	irr.	unirr.	irr.	unirr.	irr.	unirr.	irr.
S7C15	31.2ab	44.3a	4.94a	5.56a	38.2a	51.6a	15.0a	23.0a
ST163	33.0a	54.2a	4.63ab	7.08ab	36.9ab	74.7a	14.0ab	33.5a
ST148	29.2ab	51.0a	4.60ab	7.25 b	33.8ab	68.1a	12.9ab	30.6a
ST72	28.1 b	49.6a	3.94 b	6.54ab	20.2 b	73.4a	7.4 b	32.2a
Delta View	31.2ab	54.3a	4.52ab	6.88ab	32.2ab	64.0a	12.7ab	28.2a

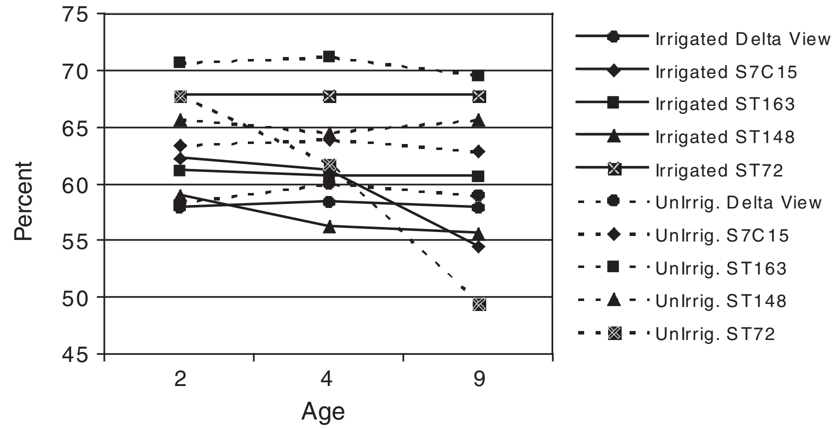

Figure 1—Percent survival by age and irrigation level for the replanted clones.

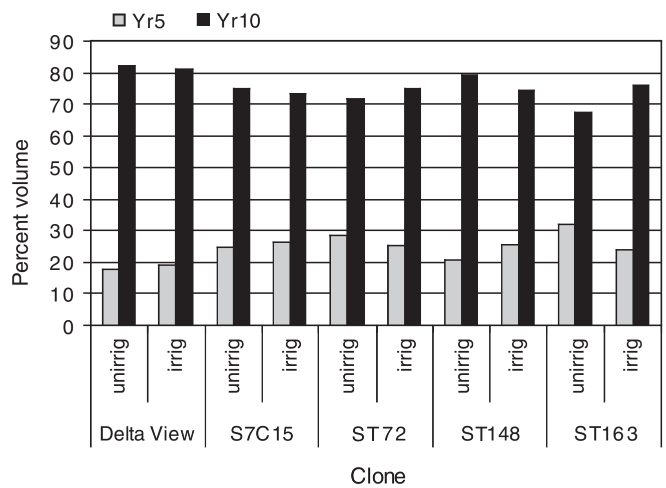

Figure 2—Percent volume growth for the replanted clones through ages 4 (year 5) and 9 (year 10).

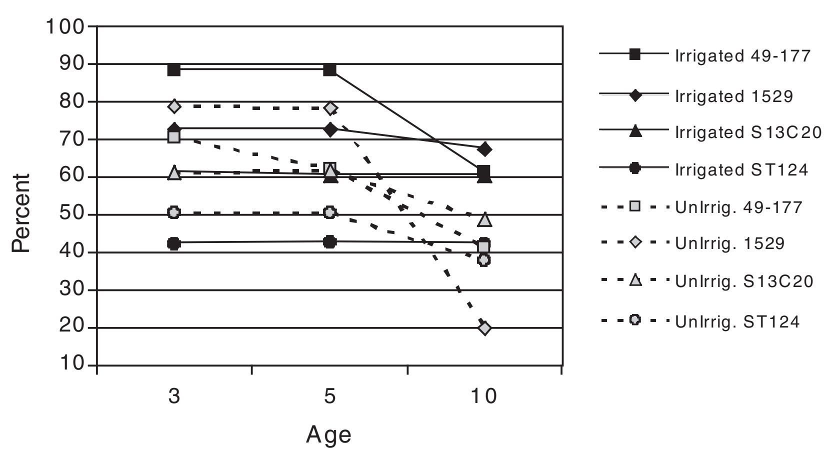

Figure 3—Percent survival by age and irrigation level for the non-replanted clones.

Table 3—Height, diameter, basal area, and biomass per acre (volume) means for non-replanted clones by irrigation level. Within each irrigation level, clonal means followed by different letters are significantly different at α=0.05

Clone	Height, feet		DBH, inches		BA, square feet per acre		Biomass, tons per acre	
	unirr.	irr.	unirr.	irr.	unirr.	irr.	unirr.	irr.
49-177	37.9a	46.3a	6.92a	6.71a	48.1a	65.6a	21.2a	28.4a
1529	32.4a	44.7a	5.98ab	6.75a	20.7 b	73.6a	8.6b	32.0a
S13C20	34.9a	56.8 b	5.50 b	7.95 b	36.2ab	92.5a	14.6ab	42.9a
ST124	33.1a	62.9 c	5.90ab	9.33 c	37.3ab	82.6a	16.1ab	40.1a

clone 49-177 trees performed best in terms of per acre biomass production, while S13C20 performed the best in the irrigated treatment. However, per acre production differences were not significant in the irrigated treatment.

Figure 4 compares percent volume growth at ages 3, 5, and 10 years for the non-replanted clones. The age 3 volume calculation is possible because d.b.h. could be measured on the non-replanted clones. For some clones (1529, 49-177) volume growth was less the second five years than the first five years. A rotation shorter than 10 years might be better for these clones. Later volume growth for clone 1529 was negative due to very poor survival. Clone ST124 had consistent low survival (fig. 3), allowing more growing space for the remaining trees, which produced more volume per tree.

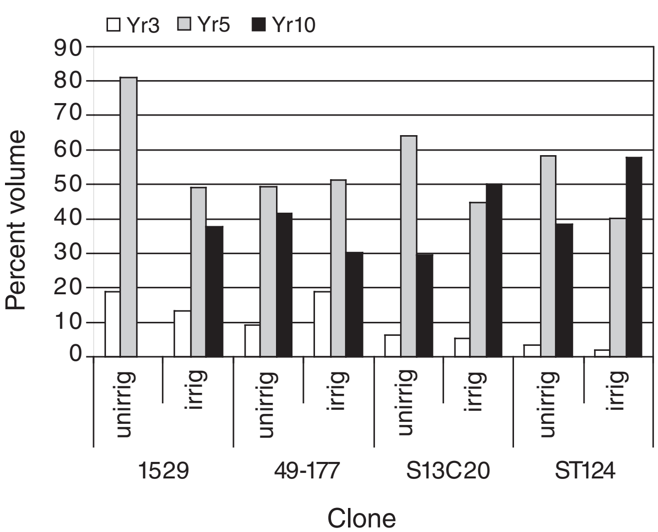

Figure 4—Percent volume growth for the non-replanted clones through ages 3, 5, and 10.

The Best Clones?

An annual growth calculation (dry tons per acre per year) can be made to compare the replanted clones with the non-replanted clones (table 4). Each group has good performers, but some clones show big treatment differences.

Table 5 lists the four best clones in each irrigation level in terms of biomass production in dry tons per acre per year. Production does not seem to be closely related to survival rate. However, the clone or clones to select for growing will likely depend on whether or not the site will be irrigated.

Economic Analysis

Growing cottonwoods for biomass must be economically attractive in order for farmers and landowners to be willing to invest in a plantation. A production rate of about 5 to 10 dry tons of biomass per acre per year is necessary (Land and others 2001). Net present values (NPV) were calculated for three of the best clones in terms of high production rates for either the unirrigated, irrigated, or both treatments. Assumptions are: (1) that existing farmland is converted and no site preparation is needed; (2) initial planting costs are $131 per acre, based on 436 cuttings planted per acre at $0.30 each; (3) irrigation costs are about $40 per year; (4) annual property taxes are $4 per acre; (5) the biomass price per dry ton is $7.50; and (6) the rate of return is 3 percent. The results are shown in table 6 below.

Growing cottonwoods for biomass could become more attractive once demand and prices increase and planting

Table 4—Mean annual biomass production, or volume growth, (dry tons/acre/year) for all clones

Replanted clones			Non-replanted clones		
Clone	unirrig.	irrig.	Clone	unirrig.	irrig.
S7C15	1.67	2.56	49-177	2.12	2.84
ST163	1.56	3.72	1529	0.86	3.20
ST148	1.43	3.40	S13C20	1.46	4.29
ST72	0.82	3.58	ST124	1.61	4.00
Delta V.	1.41	3.13			

Table 5—The four best clones in terms of mean annual biomass production (volume growth), with corresponding percent survival, by irrigation level after 10 years

Unirrigated			Irrigated		
Clone	Tons/acre/year	Survival %	Clone	Tons/acre/year	Survival %
49-177	2.12	62	S13C20	4.29	61
S7C15	1.67	64	ST124	4.00	43
ST124	1.61	51	ST163	3.72	61
ST163	1.56	71	ST72	3.58	68

Table 6—Income, expenses, and net present value (NPV) over 10 years for three of the best performing clones. Expenses were discounted to calculate net present value. The per ton price needed to break even is also shown

Parameter	Clone and irrigation level			
	ST124		S13C20	49-177
	unirr.	irr.	irr.	unirr.
Yr10 Income, $	121	301	322	159
10 yr. Expenses, $	166	525	525	166
NPV, $	(75)	(290)	(274)	(47)
Break even, $	14	17	16	11

costs are decreased. Irrigation costs must be reduced, or clones selected that perform well in particular regions without irrigation. After the first rotation, planting costs will be negligible if coppicing is used. Indications are that the Conservation Reserve Program (CRP) will cost-share short rotation woody plantations. However, weed control and fertilization costs must be considered. Some of the clones produced more biomass during their first 4 to 5 years of growth than the last five years during the 10 year rotation. For example, clone 1529 had the highest production of all clones after five years with a positive NPV requiring a breakeven price of just $6.50 per dry ton.

CONCLUSIONS

Irrigation did not affect overall survival for the replanted clones, but survival was higher for the irrigated non-replanted clones. Clonal survival varied widely within irrigation treatments, but better survival did not necessarily result in greater volume growth. Irrigation with bedding increased volume growth over the unirrigated treatment with subsoiling. Some clones exhibited greater volume production rates than others, however, volume growth overall was less than expected. Production rates of 5 to 10 dry tons per year would be required for a viable operation. The economics of growing these cottonwood clones in AR should improve with reduced growing costs (through better cultural treatments) and increased prices. Cost-share payments will also help.

Most farmers and landowners will probably want to use unirrigated lands for growing short rotation woody energy crops. Additional research to refine cultural treatments such as spacing, rotation length, weed control, and fertilizer, along with further testing of these and other cottonwood clones, will be needed. Much of this work has been done in other regions of the United States, but little information exists for AR.

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ROOTING STEM CUTTINGS OF NORTHERN RED OAK (*QUERCUS RUBRA* L.) UTILIZING HEDGED STUMP SPROUTS FORMED ON RECENTLY FELLED TREES

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Abstract—The ability to root stem cuttings collected from hedged stump sprouts formed on recently felled trees was evaluated for 26 codominant northern red oak (*Quercus rubra* L.) trees growing in Durham County, NC. Sprouting occurred, the same year as felling, on 23 of the 26 tree stumps and sprout number was significantly and positively correlated with stump diameter. The following year the stump sprouts were pruned to 20 cm and allowed to produce one new flush of growth. Fourteen of the 23 tree stumps produced a suitable number of stem cuttings to be evaluated for rooting ability. Stem cuttings collected from these 14 tree stumps rooted in percentages ranging between 35 and 100 percent. Stem cuttings from 11 of the 14 tree stumps in this study rooted at 65 percent or higher. Rooting percentage was significantly and negatively correlated with tree age. In general, as tree age increased rooting percentage decreased. However, stem cuttings from six trees between the ages of 20 and 45 years rooted at 100 percent. First year overwintering survival for the newly rooted stem cuttings was 71.5 percent. At the end of the second growing season a sub-sample of the rooted cuttings had an average height of 54 cm and an average root collar diameter of 9.7 mm.

INTRODUCTION

Regenerating natural hardwood timber stands in upland regions of eastern North America with northern red oak (*Quercus rubra* L.) as a significant component, has proved challenging to foresters. Two major limitations to such regeneration efforts are the lack of advance northern red oak (NRO) regeneration in preharvested or predisturbed stands and the slow growth and high mortality rates of existing advanced NRO regeneration after canopy removal as a result of intense herbaceous and woody competition. In some cases, this regeneration dilemma has been addressed by employing artificial regeneration techniques, such as plantation systems and enrichment plantings.

Planting stock utilized in these systems is commonly obtained from bare-root nurseries growing seedlings from unimproved, bulk collected acorns. Efforts to genetically improve NRO planting stock exist, but have been limited largely due to the costs associated with relatively long periods of juvenility, episodic acorn crops, abundant acorn predators, and long-term progeny trials (Robison and others 2004). However, recent advances in the vegetative propagation of NRO by means of rooting stem cuttings may offer a viable alternative to conventional oak improvement practices by improving growth rates, consistency, and quality of artificial planting stock. In most oak rooted cutting studies, rooting juvenile stem material has provided the best results. For detailed discussion on efforts to vegetatively propagate stem cuttings of NRO, see Dreps (2007), Drew and Dirr (1989), Fishel and others (2003), Teclaw and Isebrands (1987), and Zazcek and others (2006).

In this study, we report on an effort to vegetatively propagate juvenile stem cuttings of NRO collected from stump sprouts of 14 recently felled trees ranging in age from 18 to 62 years. Though successfully accomplished by Duncan and Matthews (1969) for southern red oak (*Quercus falcata* L.) and water oak (*Quercus nigra* L.), the only reported effort to root stem cuttings collected from stump sprouts of NRO (Fishel and others 2003) was not successful. The ability to root stem cuttings of NRO stump sprouts would allow tree selection for cloning based on identification of phenotypically superior individuals.

Once selected and cloned post-rooting cultural practices aimed at optimal first year overwintering survival and second year nursery growth of the rooted cuttings are necessary. Select genotypes could be multiplied by means of serial propagation, utilizing similar techniques employed in rooting stem cuttings of oak from hedged seedlings (Dreps 2007).

METHODS

In January 2003, 26 codominant NRO trees growing in the North Carolina State University Hill Forest in central NC (Durham County) were chainsaw felled and allowed to stump sprout during the subsequent growing season. Cut trees ranged in age from 12 to 70 years and 4 to 34 cm in basal diameter. Each tree stump was encircled by wire screening to protect sprouts from browsing. In February 2003, the total number of sprouts per tree stump was counted and all sprouts were cut to 20 cm above the stump to stimulate new growth. Three trees did not produce any sprouts. On May 25, 2004, after a single, fully developed flush of new shoot growth had formed on the pruned stump sprouts, 15-cm terminal stem cuttings were collected. Only 14 of the 23 tree stumps with pruned stump sprouts produced an adequate supply of stem cuttings (> 20) during 2004 to be included in the rooting study. These 14 trees ranged in age from 18 to 62 years and had a basal diameter ranging from 10 to 34 cm.

The cuttings were prepared for rooting and stuck in rooting containers the same day as collection (May 25, 2004). The cuttings were prepared by removing the leaves and petioles from the lower half of each cutting, recut at the base, and dipped 2 cm deep into a liquid solution of 1 percent IBA (Indole-3-butyric acid)/50 percent EtOH (95 percent). After allowing the bases to dry for one minute, the cuttings were stuck 4 cm deep into rooting containers (Ray Leach SC-10 Super Cell Cone-tainers™, Stuewe and Sons, Inc. Corvallis, Oregon) filled with a moist media mixture of 3

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peat: 2 perlite: 1 vermiculite (v/v/v). Rooting occurred in a misting chamber covered with a shade cloth (55 percent of ambient light) and constructed around propagation tables in a shaded, polyethylene-covered, Quonset-styled greenhouse. Combined the greenhouse and rooting chamber provided 15 percent of ambient light within the rooting chamber. Overhead mist irrigation was provided initially to the cuttings every 12 minutes for 15 seconds for the first 50 days and then gradually tapered until day 75. Sticking techniques and rooting environment conditions for stem cuttings of northern red oak are described in greater detail in Dreps (2007).

The rooting study was a randomized complete block design with four replications of five cutting row plots per individual tree genotype (n=14). Rooting percentage was assessed after 75 days on August 7, 2005 as indicated by live tops and roots projecting from the bottom of the container or live cuttings resistant to being pulled from their containers.

Following rooting, the cuttings were acclimated to a greenhouse environment without mist. On August 21, 2004 after two weeks of acclimation, 56 of the rooted cuttings were placed outside in a shaded (70 percent of ambient light), open-air structure and hand watered every two days. In December the rooted cuttings were moved into an unheated overwintering house to protect them from winter ice and wind and hand watered twice a month until bud break the following spring.

On May 5, 2005, overwintering survival was assessed. The rooted cuttings were considered successfully overwintered if they broke bud and produced new shoot growth. On the same day, 16 successfully overwintered rooted cuttings were transplanted into 6.23 L Treepot2™ (Stuewe and Sons, Inc., Corvallis, Oregon) containers filled with composted pine bark and top dressed with 29.5 c.c. of Nutricote Total (13-13-13) slow release fertilizer (Chisso-Asahi Fertilizer Co., Tokyo, Japan). The rooted cuttings were then placed under shade (70 percent of ambient light), hand watered every two to three days, and allowed to grow for the remainder of the 2005 growing season. On November 16, 2005, shoot height and root collar diameter were measured in order to provide a morphological assessment of northern red oak rooted cutting stock quality after two years of container growth.

STATISTICAL ANALYSIS (2003-2004)

Correlation analysis of stump sprout number, rooting percentage, age, and stump diameter during the 2003 and 2004 growing seasons were performed with the correlation procedure in SAS (SAS Institute, Cary, NC). Analysis of variance (ANOVA) for rooting percentage was conducted using the general linear model procedure in SAS and included both fixed (genotype) and random (replication) factors and their interactions. When ANOVA results indicated rooting percentage differences ($p< 0.05$) among genotypes, Duncan's multiple range test was used to separate the means at $p<0.05$.

RESULTS AND DISCUSSION

Stump Sprout Production

Twenty-three of the 26 trees felled in 2003 produced stump sprouts. Of these 23 trees, sprout number was significantly ($p=0.0035$) and positively correlated ($r=0.58$) with stump diameter. For these same trees, however, age was not significantly correlated ($p=0.2723$) with sprout production. Age is often considered a poor sprout predictor because of weak correlations with stump diameter (Wendel 1975). Similarly, in the current study stump diameter was not significantly correlated ($p=0.088$) with tree age. The 23 tree stumps evaluated in this study ranged in diameter from 4 to 34 cm, were between 12 and 62 years of age, and produced between 2 and 50 sprouts. Lynch and Bassett (1987) found that sprouting was greatest for felled NRO trees in the 12.7 to 20.3 and 22.9 to 30.5 cm diameter classes, while declining in larger diameter classes. Nine trees in our study had stump diameters smaller than these two diameter classes, 12 were within these two categories, and two had stump diameters larger than Lynch and Bassett's diameter categories. On average these three groups produced 13, 26, and 32 sprouts, respectively.

Stem Cutting Production and Rooting Percentages

The number of new shoots produced in 2004, following pruning, was not determined. However, 14 of the 23 trees with pruned stump sprouts produced more than 20 new shoots each. Rooting percentages for stem cuttings collected from these 14 trees varied significantly according to tree ($p= <0.0001$), averaging 78 percent and ranging from 35 to 100 percent. Rooting percentage was significantly ($p=0.0497$) and negatively correlated ($r = - 0.53$) with tree age, but was not significantly ($p=0.879$) correlated with stump diameter.

Several NRO studies demonstrate high rooting percentages for juvenile stem cuttings obtained from hedged seedlings (Dreps 2007, Zaczek and others 2006). Stump sprouts also represent juvenile plant material (Johnson and others 2002) and therefore, it was expected that cuttings collected from pruned stump sprouts would also root in high percentages. Eleven of the 14 trees in this study rooted at 65 percent or higher. Even though rooting was only 35 percent for one tree, this percentage may still be adequate to move the genotype into a serial propagation system. Additional research should be undertaken to determine if poor rooting stump sprouts pass on this trait during serial propagation.

The negative correlation between tree age and rooting percentage partially explained the range of rooting percentages among these 14 trees. Cuttings collected from the oldest (62 years) and youngest (18 years) two trees in this study rooted at significantly different percentages, 55 and 95 percent, respectively. Six trees, however, ranging in age from 20 to 45 years, rooted at 100 percent. Though this outcome somewhat suggests decreased rooting with advanced age, a larger sample size may provide a more accurate picture of the relationship between tree age and rooting.

Overwintering Survival and Second Year Growth

The overall survival rate for the 56 rooted cuttings placed in the overwintering house following rooting was 71.5 percent. Some researchers have suggested that forcing treatments (e.g., a period of post-rooting growth in a greenhouse under warm temperatures and extended day length) are necessary to promote high rates of overwintering survival for several woody plant species. Dirr and Heuser (1987) hypothesized that forcing treatments allow newly rooted cuttings to replenish carbohydrate reserves that may be lacking immediately following root formation. However, Dreps (2007) found no difference in first year overwintering survival between NRO rooted cuttings subjected to a 74-day forcing treatment prior to overwintering and those not receiving a forcing treatment.

Average height and root collar diameter for the 16 rooted cuttings transplanted into larger containers and grown for a second year in 2005 were 54.1 cm and 9.7 mm, respectively. Above ground, these plants were morphologically similar to well cultured 1-0 bare-root seedlings. Below ground, however, their root systems were more branched and fibrous than most NRO bare-root seedlings.

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WHITE OAK EPICOTYL EMERGENCE AND 1-0 SEEDLING GROWTH FROM SURGICALLY ALTERED GERMINATING ACORNS

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Abstract—Open-pollinated white oak (*Quercus alba* L.) acorns were collected and stored at 4 °C in November 2004. Three days before sowing in early December, we treated germinating acorns in five ways: no surgery (C); one half of the radicle cut off (HR); whole radicle cut off (WR); one cotyledonary petiole severed (OP); and both cotyledonary petioles severed, which resulted in no embryo axis (NE). Seedlings were lifted in February 2006. The NE treatment had two percent epicotyl emergence and was not included in our statistical analysis. The OP seedlings were shorter and had greater root-to-shoot ratio than seedlings in other treatments. For most of the families, the OP treatment had less percent epicotyl emergence; OP seedlings also had smaller root collar diameter and less biomass than C. More HR and WR seedlings had a forking root system than C. Our study showed that white oak acorns should be sown before radicle protrusion to avoid damage, which may reduce growth or result in loss of the epicotyl.

INTRODUCTION

White oak (*Quercus alba* L., WO) is among the most valuable and abundant oak species in the Eastern United States. It often coexists with northern red oak (*Q. rubra* L.) in natural stands. The number of both species is declining, and their prominence on high-quality mesic sites has diminished throughout their ranges due to lack of adequate natural regeneration. Artificial regeneration of oaks has not been successful on those sites due to severe competition from faster growing or more shade tolerant species. The absence of quality oak planting stock is another reason given for the regeneration failure (Kellison 1993, Lorimer and others 1994).

Since the early 1990s, scientists and staff officers from the USDA Forest Service Southern Research Station, Southern Region, and the Georgia Forestry Commission have developed and implemented an integrated artificial oak regeneration program. The program's purpose is to establish oak seedling plantings on several national forests in the Southeastern United States, in order to meet land management goals and objectives (Kormanik and others 1994, 2000, 2002, 2006). The goal of an integrated regeneration program is to establish seed-production areas, to obtain desirable stocking in reforestation areas, and to augment species composition in such areas. Attributes of successful oak stand establishments are good survival, fast growth, and early acorn production. Growing and selecting the bareroot oak seedlings that possess the most desirable root system and stem characteristics, as well as protecting planted stands from competition for several years after establishment, will help ensure success (Clark and others 2000, Kormanik and others 1997, 2002, 2004, 2006). A full cycle of this artificial regeneration program begins with acorn collection, handling, and storage. The next phases in the program include growing, grading, and outplanting seedlings, as well as selecting, preparing, and maintaining sites. Such a program results in fully stocked oak stands that can be used for timber, wildlife, or aesthetic purposes, as well as sites from which to collect acorns for future stands (Kormanik and others 2006).

Among many successful applications of this regeneration program, however, some failures also came to light. In some cases the lack of effective and timely vegetation-control regimes in planted stands may have caused stand establishment failures (Kormanik and others 2004, 2006). Sometimes, due to errors in acorn collection and storage prior to sowing, the entire seedling crop was discarded at the nursery. This was especially true with WO (Kormanik and others 2000, Sung and others 2002, 2006). White oak acorn germination is highly sensitive to acorn desiccation (Connor and Sowa 2003, Sung and others 2006), and WO acorns with less than 30 percent moisture content had less than 12 percent germination (Sung and others 2006). Nevertheless, WO acorn moisture contents at sowing did not affect subsequent seedling growth in the study by Sung and others (2006). Factors other than low acorn moisture contents at sowing must be contributing to poor WO seedling growth in the nursery (Kormanik and others 1997, Sung and others 2002).

Unlike the red oak species group, acorns from the white oak species group do not need stratification to germinate. It is commonly observed that WO acorns germinate during storage at 4 °C. After the radicle extends, the germinating WO acorn extends its cotyledonary petioles out of the acorn fruit pericarp between which the epicotyl (future shoot) eventually extends. The protruding parts of the germinating acorns are vulnerable to physical damage during acorn storage, handling and sowing. Our study objective is to evaluate the effects that varying degrees of physical damage to the radicle and the cotyledonary petioles of WO acorns prior to sowing have on epicotyl emergence and subsequent seedling growth.

MATERIALS AND METHODS

Preliminary Study

White oak acorns were collected from a mother tree in Athens, GA within 24 hours after dropping. The acorns were soaked in water for 30 minutes. All floating acorns and

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acorns with holes, cracks, or any signs of blemish were discarded. The rest were placed in moistened paper towel-lined Pyrex glass pans, covered with plastic wrap, and set on laboratory benches. Temperatures in the laboratory were kept between 25 and 28 °C. When most acorns had the radicle (less than 2 cm) and two cotyledonary petioles (less than 1.5 cm) protruding, we imposed surgical treatments on the germinating acorns. The five treatments were: no surgical treatment (C); radicle cutoff at half the distance between the radicle tip and the base of the hypocotyl, which had a slightly darker color than the radicle (HR); whole radicle cutoff (WR); one cotyledonary petiole severed at 1 cm from where it connects with the embryo axis (OP), and both cotyledonary petioles severed at 1 cm from the embryo axis, resulting in acorns with no embryo axis (NE). Each treatment had 30 acorns. Acorns from each group were then placed into glass pans lined with fresh moist towels. One week later, we assessed morphological development of the embryo axis. We took no measurements of radicle or epicotyl growth in this preliminary study.

Field Study

In early November 2004, WO acorns were collected within 24 hours after dropping from seven mother trees in Athens, GA. The same procedures for floating and selecting acorns were followed as in the preliminary study. A sub-sample of 50 acorns was randomly selected from each family for moisture content determination (Sung and others 2006). Acorns from all seven families had a moisture content of at least 43 percent, indicating the absence of desiccation. The rest of the acorns were stored at 4 °C until 3 days prior to sowing. Most acorns had radicle and cotyledonary petiole protrusion on the day of surgical treatments. However, acorns from families 2 and 5 did not have much radicle or cotyledonary petiole protrusion to permit surgical treatment. These acorns were brought out of the cold storage and set at room temperature one week before surgical treatment to promote radicle and cotyledonary petiole extension. We then implemented the same surgical treatments as we had in the preliminary study. All treatments were completed within 10 h. Within a family, acorns of similar sizes were evenly distributed over the treatment groups to avoid size-associated variations among treatments (Kormanik and others 1998). After the surgical treatments, all acorns were carefully placed in plastic bags and stored at 4 °C until sowing. Acorns were sown the first week of December, 2004, at the Georgia Forestry Commission's Flint River Nursery (near Montezuma, GA) and grown using the standard oak nursery protocol for WO (Kormanik and others 1994, 2000). Epicotyl emergence was scored at the end of April 2005, and 1-0 seedlings were lifted in February 2006. Because the extent of leaf abscission varied greatly among seedlings within the same family and among families, we removed all remaining leaves before determining stem and branch dry weight. Seedling flush number, stem and branch oven dry weight, root system oven dry weight, and forking root system were recorded. Seedlings with taproots that forked within 7.5 cm beneath root collar were counted as having a forking root system. As in a study by Sung and others (2002), the flush elongated from the resting bud of the epicotyl was counted as the first flush.

Experimental Design and Statistical Analysis

The field study was conducted as a split-plot design with replication by means of four blocks. For logistic reasons, acorns from each family were planted together in each block with treatment groups randomly assigned within the family whole plot. Within each block, all seven families were randomly assigned. A total of 720 acorns (36 acorns per treatment x 5 treatments x 4 blocks) from each of the seven families were sown. Distance between treatment subplots, family whole plots, and blocks was 1 m. The whole-plot factor was family and the split-plot factor was treatment. The family and treatment factors and their interaction were considered fixed effects. The NE treatment had very low percent of acorns with epicotyl emergence, thus this treatment was not included in the statistical analyses involving seedling growth or morphological parameters. The split-plot design was a mixed model which was analyzed using PROC MIXED (SAS 2004) where the 0.05 alpha level was used for all tests on the main effects and interaction. The multiple comparisons for the four treatments within a family were performed using the Bonferroni method, where the six comparisons within a family were each tested at the 0.05/6=0.0083 level. The six multiple comparisons were performed across families when there were no treatment x family interactions. The six multiple comparisons were performed within each family when there were treatment x family interactions. No other multiple comparisons were of interest.

RESULTS AND DISCUSSION

During surgical treatment for both preliminary and field studies, the two protruding cotyledonary petioles from some WO acorns were no longer compressed against each other. The epicotyl of these acorns was visible but not extending at the time. White oak acorns often start germination (radicle protrusion) within days of dropping if the environmental condition is moist enough. The epicotyl usually does not extend until the temperature warms up in the spring. Germinating acorns with their epicotyl not protected by the two protruding cotyledonary petioles may be vulnerable to physical destruction and desiccation if they are not covered by leaf litter or soil throughout the winter.

Preliminary Study

Seven days after surgery, some acorns in the C group grew radicles as long as 7 cm and epicotyls as long as 2 cm. All acorns in the HR group developed one or multiple adventitious roots from the cut surface of the severed radicle. Those acorns with only a single new adventitious root were similar to the C in appearance. Epicotyl development from all HR and WR acorns was similar to that of the C. Some WR acorns grew multiple adventitious roots from the cut surface or from the lower portion (near the remaining embryo axis) of the cotyledonary petioles. Other WR acorns grew a single new root from the cut surface. The OP acorns showed no differences in epicotyl or radicle development from those of the C acorns seven days after surgery. Some NE acorns developed adventitious roots near the severed ends of the cotyledonary petioles. No epicotyl development was observed in the NE acorns but the stored reserves in cotyledons of these acorns were able to sustain adventitious root growth.

Field Study

No treatment and family interaction was observed for seedling height, flush number, or root-to-shoot ratio. There were treatment and family interactions for epicotyl emergence percent, root collar diameter, shoot and root dry weight growth, and root forking. Therefore, treatment effects were analyzed within each family for these parameters.

Epicotyl emergence—Theoretically, the NE acorns whose embryo axes were cut off should have had zero percent epicotyl emergences. However, this treatment had two percent epicotyl emergence, and all except families 1 and 4 had at least one epicotyl emerging. It is known that some oak acorns have multiple embryos. Acorns with more than one radicle protruding on the day of surgery were not used in the study. It is possible that some multiple-embryo acorns had only one embryo axis protruding at the time of surgery. These NE acorns which still had intact embryos contained within the pericarp at surgery were able to develop into seedlings of normal appearance. Indeed, values of the few NE seedlings were in the similar range as those from seedlings of other treatments (table 1). Another less likely possibility is that the severed cotyledonary petioles not only developed adventitious roots but may generate adventitious buds, which could develop into shoots as in a *Q*. *coccifera* L. and *Q*. *ilex* L. study by Pascual and others (2002).

Some of the NE acorns were excavated in June 2005. A few of these excavated acorns did not develop any recognizable adventitious roots. But most of the excavated NE acorns developed one or more adventitious roots from the lower part of one or both cotyledonary petioles. These adventitious roots ranged from 5 to 18 cm in length. Farmer (1977) described in his study that some WO acorns grew roots but not much of the epicotyl (1 to 7 cm in length). He reported as high as 50 percent of freshly collected WO acorns had this type of epicotyl dormancy (Farmer 1977). These dormant epicotyls did not have any leaf development after an eight week greenhouse culture. Our study did not support epicotyl dormancy as reported by Farmer (1977). The number of epicotyl emergence scored at the end of April was very close to the number of 1-0 seedlings lifted in February 2006. We found that the almost non-emergence of epicotyl by NE acorns was directly caused by severance of both cotyledonary petioles, and thus the physical destruction of epicotyls.

Table 1—Growth of 1-0 white oak seedlings from surgically altered germinating acorns. Surgical treatments were: C-control, HR-half radicle cutoff, WR-whole radicle cutoff, OP-one cotyledonary petiole severed, and NE-both cotyledonary petioles severed resulting in no embryo axis

Treatment	HT	Flush	Root shoot ratio
	cm	#	
C	28.9a[b]	2.79ab	4.77b
HR	30.4a	2.85a	4.60b
WR	29.7a	2.78ab	4.68b
OP	22.5b	2.67b	5.29a
NE[a]	22.8	2.70	4.52

[a]Due to low epicotyl emergence percent for this group, its growth parameters were not included in the statistical analysis.
[b]Least square means with the same letter for a given variable were not significantly different at the 0.05 level using the Bonferroni method.

All the acorns we used were collected and stored properly as evidenced by a close to 100 percent of radicle protrusion, which of course was the basis for this study. However, epicotyl emergence of C acorns varied from 28 percent in family 3 to 75 percent in family 4 (fig. 1). The reasons for this less than satisfactory percent of epicotyl emergence were not clear. As mentioned previously, the separation of two cotyledonary petioles before sowing, which makes the non-protected epicotyl more vulnerable, may be one reason for the low percent of epicotyl emergence. Excavation of the non-epicotyl emerging acorns of treatments other than NE would provide some insights to this phenomenon. But excavation was not conducted in this study. Nevertheless, results in figure 1 support earlier observations made by Kormanik and others (1997) and Sung and others (2002, 2006) that many factors in addition to acorn moisture content can impact WO epicotyl emergence and subsequent seedling growth.

Treatment effects on epicotyl emergence were not consistent across families (fig. 1). Radicle treatments (HR and WR) did decrease epicotyl emergence for four families, and removal of one cotyledon (OP) reduced epicotyl emergence for three of the seven families. These results indicated that it is best to machine sow WO acorns before radicle and cotyledonary petiole protrusion to avoid radicle or cotyledonary petiole severance that results in growth reduction or epicotyl destruction. Hoss (2006) reported that most of the swamp white oak (*Q*. *bicolor* Willd.) acorns did not germinate during 1 year storage at 1 °C. Seedlings from these long-term and low-temperature stored acorns grew as well as those from acorns sown immediately after collection (Hoss 2006). Acorns of sessile oak (*Q*. *petraea* (Matt.) Liebl.), another white oak species, did not germinate during the 6 month storage at -1 °C (Zitnik and others 1999). It would be interesting to test whether WO acorns can be stored at 1 °C or -1 °C to prevent radicle and cotyledonary petiole protrusion and still retain viability.

Growth of 1-0 seedlings—The OP seedlings, fed by one cotyledon before they became photo-autotrophic, were shorter than C, HR, and WR seedlings (table 1). Seedling heights for the other three treatments did not differ from each other (table 1). Flush number of the OP seedlings was less than that of the HR seedlings (table 1). Between 62 and 64 percent of seedlings in C, HR, and WR treatments had three or more flushes and only 56 percent of the OP seedlings had three or more flushes. Total flush number for all seedlings in this study (table 1) were generally one less than that reported by Sung and others (2002).

The OP seedlings in all but families 1 and 3 developed smaller root collar diameter (fig. 2), had less stem and branch

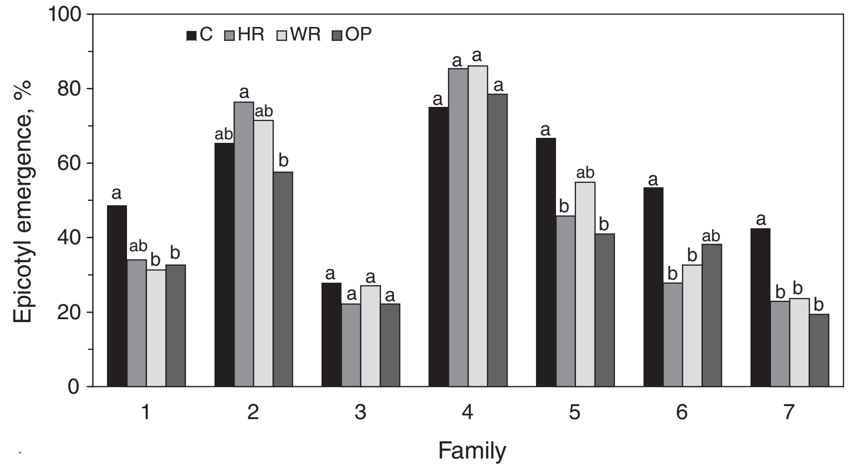

Figure 1—Within-family comparisons of epicotyl emergence as affected by surgical treatments of germinating white oak acorns. Surgical treatments were: C- control, HR-half radicle cutoff, WR-whole radicle cutoff, and OP-one cotyledonary petiole severed. Within each family, bars with the same letter are not significantly different using the Bonferroni method, where the six comparisons within a family were each tested at the 0.05/6=0.0083 level.

dry weight (fig. 3), and root dry weight (fig. 4) than C, HR, and WR seedlings. The effect of cotyledon reserve amount on seedling growth was still evident even after seedlings have become photo-autotrophic. This observation agreed with the report that within a half-sib northern red oak family, large-sized acorns (with more cotyledon reserve) always produced larger 1-0 seedlings than smaller-sized acorns (Kormanik and others 1998). Similar result of acorn size positively affecting seedling growth was reported with *Q. rugosa* L. (Bonfil 1998). In the Bonfil (1998) study, removal of both cotyledons one month after germination had a negative impact on that species' survival and growth after one growing season.

During the first year of seedling growth and development, WO allocated more than three-fold the amount of dry weight biomass to root systems than to stems and branches. The root-to-shoot ratio would be lower if leaf dry weight were included as a part of the shoot dry weight. Sung and others (1998) reported root-to-shoot ratios of 1.86 and 3.27 with and without leaf weight included in shoot dry weight, respectively. The root-to-shoot ratio for OP seedlings was significantly greater than seedlings of the other three treatments (table 1). These data suggest that when the carbohydrate supply is limiting, WO roots exhibited even greater sink strength for carbohydrate over the stems.

In general, seedlings of HR and WR treatments did not differ from C in most of the growth parameters assessed (table 1, figs. 2, 3, and 4) except for having more seedlings with forking root systems (fig. 5). This result was the opposite of findings published by Barden and Bowersox (1991). They found that clipping off one half length of the radicle slightly increased northern red oak seedling height growth during the first year. Their study did not assess root forking. Despite a slight increase in growth that results, this practice is not operationally practical.

In our study, fewer than eight percent of C seedlings from all but family 2 had forking roots. In family 2, 27 percent of C seedlings had forking roots. Yet, seedling biomass for C

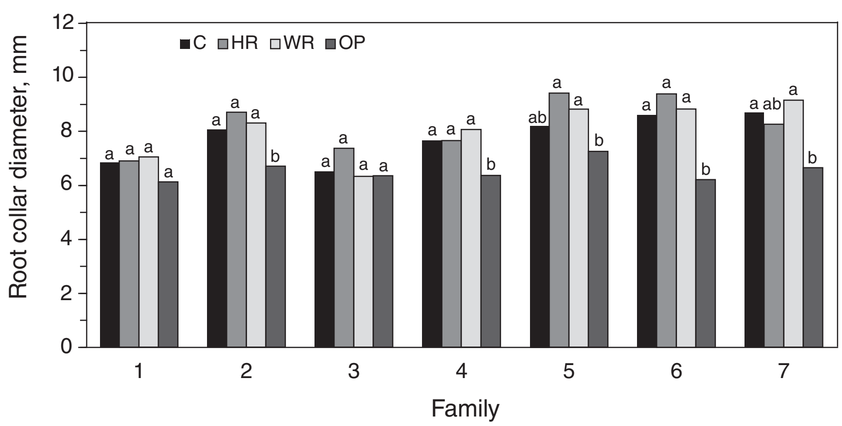

Figure 2—Within-family comparisons of root collar diameter of 1-0 seedlings from surgically altered germinating white oak acorns. Treatments and statistical analyses were the same as in Figure 1.

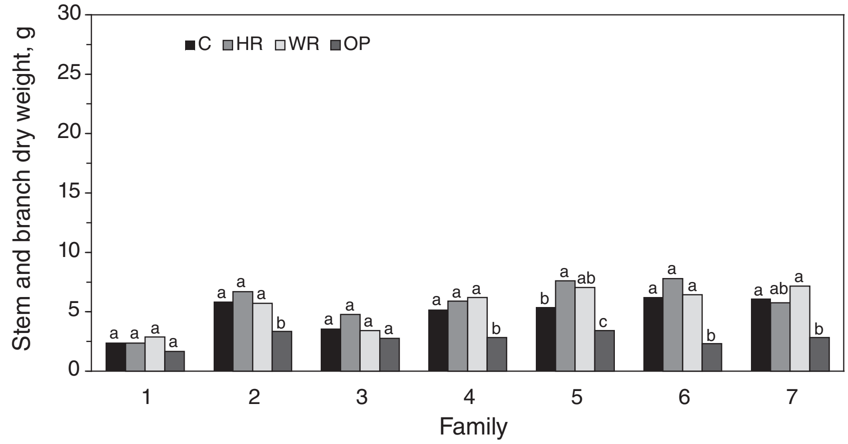

Figure 3—Within-family comparisons of stem and branch dry weight of 1-0 seedlings from surgically altered germinating white oak acorns. Treatments and statistical analyses were the same as in Figure 1.

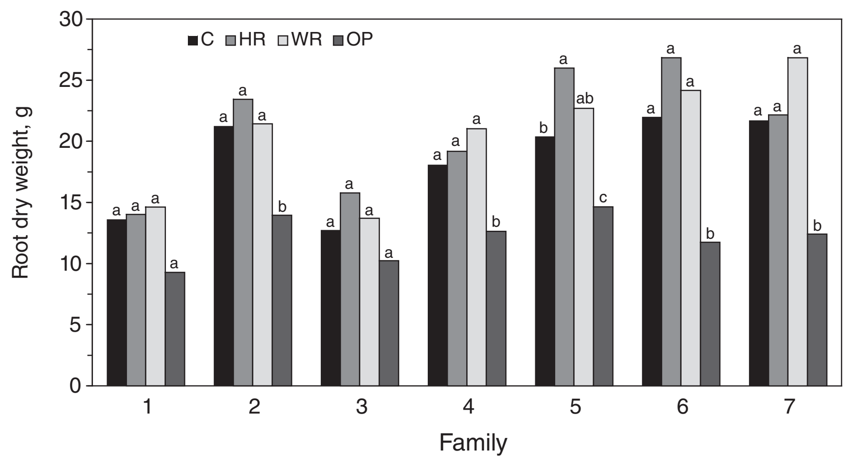

Figure 4—Within-family comparisons of root dry weight of 1-0 seedlings from surgically altered germinating white oak acorns. Treatments and statistical analyses were the same as in Figure 1.

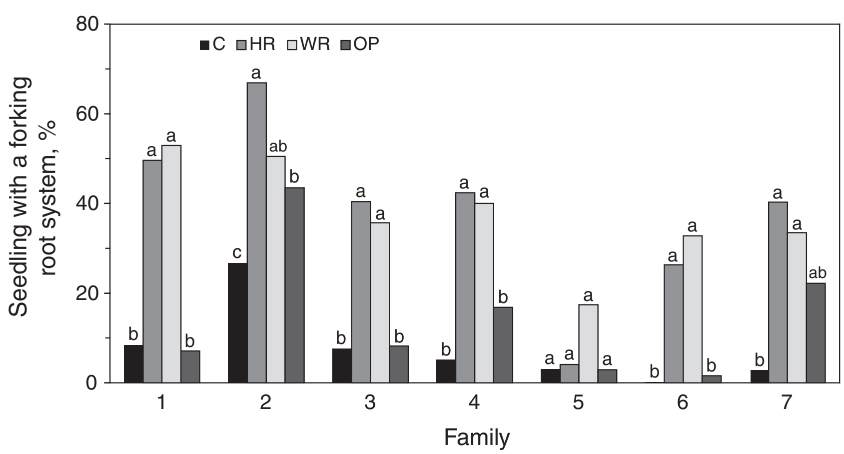

Figure 5—Within-family comparisons of root system forking of 1-0 seedlings from surgically altered germinating white oak acorns. Treatments and statistical analyses were the same as in Figure 1.

seedlings of family 2 was among the greater ones in all C seedlings from all families (figs. 2, 3). These results indicate that a forking root system is partially controlled by genetics, but that the physiological impact on seedlings is not clear. Tamasi and others (2005) reported that forking root systems negatively affect the physical stability of trees in areas where high wind can uproot or topple trees. Seedlings with forking root systems also are more difficult to plant with standard planting bars and augers, and may leave seedlings more susceptible to desiccation due to air pockets that can be left around the root system after planting.

CONCLUSIONS

There was much variation in WO seedling growth within each family and within each treatment. But the basic biology of the first year WO seedlings, such as the greater dry weight allocation to roots than to shoots remains the same across treatments and families. Oak acorn cotyledon reserves were critical for 1-0 seedling growth. Some WO acorns developed adventitious roots even when their embryo axes were removed. Any factors, such as desiccation or physical damage, which affect an epicotyl, will result in no shoot emergence. For operational purposes, it is best to machine sow WO acorns before radicle and cotyledonary petiole protrusion to avoid cotyledonary petiole severance that results in growth reduction or no epicotyl emergence. This means that the nursery personnel need to get the nursery beds ready in time for sowing non-protruding WO acorns.

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SUCCESS OF RIPARIAN RESTORATION PROJECTS IN THE MOUNTAINS, PIEDMONT, AND COASTAL PLAIN OF VIRGINIA

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Abstract—Forested riparian buffers are a Best Management Practice (BMP) for protection of water quality and for habitat. Since the 1990s, conservation agencies in Virginia have been involved in establishment of riparian buffers under the auspices of programs such as the Conservation Reserve Enhancement Program (CREP). Although CREP was established for protection of water quality, little monitoring has evaluated the success of establishment efforts. In summer 2006, we evaluated 63 CREP sites located in the Coastal Plain, Piedmont, and Ridge and Valley regions. Overall, riparian forests in the Coastal Plain and Piedmont were well stocked due to a combination of planted and natural regeneration. In general, the Ridge and Valley sites were not well stocked and sites had problems with invasive, exotic species. Our findings indicate that additional efforts should be made to ensure fencing is maintained, species selections are based on site conditions, and invasive species are controlled.

INTRODUCTION

Riparian forests have numerous societal values including the protection of water quality (shade, nutrient uptake, storage and transformation, sediment trapping, streambank stability, and detritus/course woody debris export) and habitat (linear corridors, landscape diversity, stream habitat) (Castelle and others 1994, Daniels and Gilliam 1996, Klapproth 1996, Verry and others 2000, Walbridge 1993, Welsch 1996).

Approximately 87 percent of the riparian forests in the Eastern United States have been deforested, primarily for agricultural production (Allen and others 2001). Over the past decade numerous programs have been developed for restoration of these important riparian ecosystems on areas that had previously been deforested for agricultural or urban activities (Allen and others 2001). Agricultural use includes crop production, livestock grazing, and open pasturelands. These agricultural lands provide significant amounts of nonpoint source pollution to the watersheds draining into the Chesapeake Bay as well as the southern rivers of the United States. Excessive nutrients from livestock wastes, sediment runoff of erodable grounds, and runoff from chemical applications are all examples of contaminants exuded from agricultural lands (Gianessi and others 1985).

The reestablishment of riparian forests is an agricultural Best Management Practice that is often recommended for the improvement of water quality and the establishment of habitat. Several federal conservation programs exist that attempt to entice farmers to remove acres of land adjacent to watersheds from production to be used for the reestablishment of riparian forests. The Virginia Department of Forestry (VDOF) has been involved in hundreds of restoration projects in the agricultural setting. In 2004-2005 the VDOF established over 600 miles of riparian forests, primarily as part of the Conservation Reserve Enhancement Program (CREP) plantings. However, they are concerned because they have little data to document that the reestablishment plantings have survived.

The goal of this project was to examine restoration plantings across the Coastal Plain, Piedmont, and Ridge and Valley regions of Virginia in order to determine which species survived best, which planting techniques worked best, and if the plantings are adequately stocked.

METHODS

Study Site

The study sites were selected randomly from VDOF conservation programs database. Selections were weighted based on the total amount of acres planted in each physiographic region. A total of 63 sites were sampled, 16 in the Coastal Plain, 23 in the Piedmont, and 24 in the Ridge and Valley physiographic regions of VA. Sites were typically located adjacent to ephemeral, intermittent, or perennial streams, in agricultural settings and parallel to crop production fields or livestock grazing fields.

Field Methods

County VDOF foresters provided information from landowner files pertaining to the selected sites visited in the study. These files were examined for information such as the planting density, species planted, contractor information, year planted, age of planted seedlings, site preparation treatments, competition control, establishment techniques (planting tubes, planting mats, fencing), and maps of the site locations. In addition, landowners, when available, were interviewed regarding any maintenance or replanting conducted on the site and the number and type of grazing animals located near the site.

Field data at each site were collected using fixed area plots. The sample plot size was dependent upon the size of the site; the plots used in the study ranged from 1/1000th acre to 1/10th acre. For each plot the radius, landform (floodplain, toe slope, terrace, sideslope, upland), distance from stream (if applicable), and herbaceous competition data were recorded. The type, size, and color of any planting tubes used at each site were recorded for each tree. The adequacy of any

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fencing structures was also noted. The stream periodicity, when applicable and present, was identified as perennial, intermittent, or ephemeral. Individual tree data for both planted and volunteer species were recorded at each plot. Individual tree data consisted of recording the use of any planting aids (tubes, mats, or fencing), tree or shrub species, vigor (dead, poor, moderate, good), height (feet), diameter at breast height (inches, where applicable), and any comments indicating important information associated with the plot.

Statistical Analysis

Data collected in this study were analyzed using Minitab 14 Statistical Analysis Program, and Number Cruncher Statistical System. Using the data collected from the 63 sites the response variables such as tree stocking and growth characteristics were analyzed by region using the Kruskal-Wallis One-way ANOVA procedure.

RESULTS AND DISCUSSION

The Coastal Plain region had the highest stocking of planted trees with a mean of 115 trees per acre and the highest average naturally regenerated species of 3 162 per acre (table 1). These means decreased as the study sites progressed westward across the state through the Piedmont and Ridge and Valley regions. The Piedmont averaged 99 trees per acre of surviving planted trees and an average 1 082 trees per acre of volunteers, while the Ridge and Valley produced averages of 85 and 185 trees per acre, respectively. The average percent stocking for the Coastal Plain, Piedmont, and Ridge and Valley were 100, 90, and 77 percent, respectively. The percent stocking was based on the Natural Resource Conservation Guideline of planting 110 trees per acres. In combination with the planted stems, the Coastal Plain and Piedmont are very well stocked and should provide good composition throughout the establishment and growth of the stand (tables 2, 3). However, the Ridge and Valley region generally had poor stocking and efforts need to be applied to provide better survival and stocking rates. One characteristic attributing to this region's lack of stocking is the lack of a volunteer seed source. Many of the sites planted in the Ridge and Valley were in the middle of large pastures where trees, especially the pioneer species, were absent.

Several difficulties were encountered throughout the study; one commonly being the lack of information pertaining to the original species planted and their location on the planted sites. The mean stocking values for species listed in table 2 are solely based on the species that were present and identifiable during the study. The planted species, having lower stocking values in each region, were most commonly soft mast species including: black cherry (*Prunus serotina*), common apple (*Malus* spp.), crab apple (*Pyrus coronaria*), flowering dogwood (*Cornus florida*), hackberry (*Celtis occidentalis*), persimmon (*Diospyros virginiana*), and redbud (*Cercis canadensis*). The species having the best stocking for each of the regions were oaks. The best performers in the Coastal Plain region were black oak (*Quercus velutina*) and willow oak (*Quercus phellos*) (both ranked in first place). These species were followed closely by pin oak (*Quercus palustris*) and white oak (*Quercus alba*), in second and third place, respectively. The top surviving species in the Piedmont were southern red oak (*Quercus falcata*), with pin oak and white oak as the subsequent survivors. The lead survivors of the Ridge and Valley region were white oak followed by northern red oak (*Quercus rubra*) and pin oak in second and third place respectively. In each region oaks made up over 60 percent of the average surviving trees. Pin oak, willow oak, white oak, and northern red oak, along with green ash were the five most commonly observed species out of the 63 sites in the study. Having this exceptional oak stocking and dominance is good for hard mast production and long-term tree cover, but if the objective is water quality improvement and protection, then faster growing species may be more desirable.

The naturally regenerated species recorded in this study present competition for nutrients, sunlight, and water for the planted species. At the same time these volunteers are a key attribute to the riparian area and the naturally regenerated species provide many of the same functions as the planted species. The Coastal Plain was excessively dominated by sweetgum (*Liquidambar styraciflua*), red maple (*Acer rubra*), and loblolly pine (*Pinus taeda*) as the first, second, and third most frequently tallied volunteers (table 3). Sweetgum comprised approximately 40 percent of the average total stocking. Sweetgum, red maple, and loblolly pine comprise over 85 percent of the mean natural regeneration in the

Table 1—Mean stocking and survival of planted and volunteer for each physiographic region studied in Virginia

Physiographic Regions	Mean planted trees/acre	Median planted trees/acre	Average percent survival	Mean naturally regenerated trees/acre	Median naturally regenerated trees/acre	Mean Total trees/ acre
Coastal Plain	115a	91a	100	3162b	928.6b	3277
Piedmont	99a	90a	90	1082ab	540a	1181
Ridge and Valley	85a	77.5a	77	185a	38.5a	270
Mean of all regions	99.6		89	1476		

*A number followed by an “a” is significantly different (alpha = 0.1).

Table 2—Mean surviving planted trees per acre by species ranked from most prevalent, 1, to least prevalent in each physiographic region studied in Virginia. Species ranked below 10 were not included

	Coastal Plain		Piedmont		Ridge and Valley	
Species	Mean trees/ acre	Rank	Mean trees/ acre	Rank	Mean trees/ acre	Rank
American sycamore (*Platanus occidentalis*)	4.6	6	0.1	21	1.8	10
Baldcypress (*Taxodium distichum*)	2.4	11	4.3	8	2.8	7
Black oak (*Quercus velutina*)	17.2	1	0.4	19	5.4	5
Chestnut oak (*Quercus prinus*)	—	—	—	—	3.1	6
Common apple (*Malus* spp.)	4.7	5	0.4	19	0.6	17
Eastern white pine (*Pinus strobus*)	—	—	—	—	1.8	10
Green ash (*Fraxinus pennsylvanica*)	2.4	11	6.2	6	7.3	4
Northern red oak (*Quercus rubra*)	2.8	10	6.1	7	11.4	2
Pin oak (*Quercus palustris*)	15.0	2	12.9	2	9.0	3
Red osier dogwood (*Cornus sericea*)	3.2	9	—	—	—	—
Southern red oak (*Quercus falcata*)	3.5	8	15.2	1	—	—
Sawtooth oak (*Quercus acutissima*)	3.6	7	7.3	5	1.5	12
Swamp chestnut oak (*Quercus michauxii*)	10.6	4	1.3	14	2.3	9
White oak (*Quercus alba*)	12.5	3	10.4	3	22.7	1
Willow oak (*Quercus phellos*)	17.2	1	10.1	4	2.7	8
Yellow poplar (*Liriodendron tulipifera*)	0.9	15	2.6	10	0.3	18
Grand Total	107	—	94	—	82	—

Table 3—Mean naturally regenerated trees per acre by species ranked from most prevalent, 1, to least prevalent in each physiographic region studied in Virginia. Species ranked below 10 were not included

	Coastal Plain		Piedmont		Ridge and Valley	
Species	Mean trees/acre	Rank	Mean trees/acre	Rank	Mean trees/acre	Rank
American sycamore *(Platanus occidentalis)*	27.6	8	3.6	20	—	—
Ailanthus *(Ailanthus altissima)*	—	—	8.8	14	41.9	1
Autumn olive *(Elaeagnus umbellata)*	—	—	0.3	29	25.0	3
Black cherry *(Prunus serotina)*	19.3	9	13.4	12	—	—
Black walnut *(Juglands nigra)*	0.3	17	8.8	14	1.7	8
Boxelder *(Acer negundo)*	4.6	14	190.4	3	35.6	2
Coralberry *(Symphoricarpos orbiculatus)*	—	—	33.6	7	4.3	7
Crab apple *(Pyrus cornaria)*	—	—	—	—	1.5	9
Eastern redcedar *(Juniperus virginiana)*	122.0	4	76.3	5	18.6	4
Groundsel tree *(Baccharis salicifolia)*	79.4	6	—	—	—	—
Hazel alder *(Alnus serrulata)*	—	—	39.1	6	—	—
Honey locust *(Gleditsia triacanthos)*	—	—	1.9	24	1.4	10
Loblolly pine *(Pinus taeda)*	441.9	3	2.3	22	—	—
Persimmon *(Diospyros virginiana)*	9.2	12	9.8	13	1.5	9
Red maple *(Acer rubrum)*	1117.7	2	264.1	1	5.8	5
Red osier dogwood *(Cornus sericea)*	—	—	—	—	4.9	6
River birch *(Betula nigra)*	16.7	11	0.3	29	—	—
Silky dogwood *(Cornus amomum)*	—	—	—	—	1.7	8
Slippery elm *(Ulmus rubra)*	—	—	22.7	9	1.1	11
Sweetgum *(Liquidambar styraciflua)*	1407.7	1	28.4	8	—	—
Waxmyrtle *(Morella cerifera)*	18.3	10	—	—	—	—
Winged elm *(Ulmus alata)*	—	—	17.4	10	—	—
Winged sumac *(Rhus copallinum)*	119.3	5	—	—	—	—
Yellow poplar *(Liriodendron tulipifera)*	65.1	7	193.5	2	—	—
Grand Total	3472	—	1128	—	154	—

Table 4—Corresponding means ranges, and percentages of multiple parameters noted at each site for each physiographic region of Virginia in the study

		Coastal Plain		Piedmont		Ridge and Valley	
		Average	Range	Average	Range	Average	Range
General Information	Size (acres)	10	1.5 - 50	12.3	1.6 - 93	10.4	2 - 30
	Age (years)	2.25	1 - 5	2.6	1 - 5	3.2	1 - 5
	Contractor planted	—	15	—	23	—	26
	Landowner planted	—	1	—	0	—	0
	Planted density	163	110 - 440	110	110	113	110 - 193
Planting aids	Use of tubes (%)	—	81.20%	—	100%	—	100%
	Use of mats (%)	—	75%	—	95.6%	—	100%
	Use of fencing (%)	—	12.5%	—	78.2%	—	92.3%
	Tube height (feet)	3.2	0 - 4	3.2	2 - 4	3.0	2 - 4
Site prep:	Mowed (%)	—	6.25%	—	8.7%	—	3.8%
	Herbicide sprayed (%)	—	12.5%	—	4.3%	—	0%
Maintenance:	Mowed (%)	—	12.5%	—	13%	—	46.1%
	Good fence maintenance (%)	—	25%	—	82.6%	—	79.2%
	Moderate fence maintenance (%)	—	—	—	4.3%	—	4.2%
	Poor fence maintenance (%)	—	—	—	4.3%	—	4.2%

Coastal Plain. The Piedmont was also dominated by red maple, where it was the most commonly regenerated species followed closely by yellow poplar (*Liriodendron tulipifera*) and boxelder (*Acer negundo*). The Ridge and Valley's most common natural regeneration were ailanthus (*Ailanthus altissima*) followed by boxelder and autumn olive (*Elaeagnus umbellata*). The Ridge and Valley has low planting survival and these data indicate that two of the most common naturally regenerated species are invasive species. Ailanthus and autumn olive are generally considered to be non-desirable invasive exotic species. Control measures, such as herbicide applications, may be necessary in order to contend with these invasives and promote the growth of the planted species or more desirable volunteer species. However, herbicide use must be judiciously applied due to the location of these plantings near streams.

Planting tubes are a common planting aid used in these hardwood plantings to protect the seedlings from vegetative competition, animal consumption, and to provide a better growing climate for the seedlings. Three planting tubes sizes were found on the study sites. These tube sizes included 2-, 3-, and 4-foot tubes along with three sites in the Coastal Plain where no tubes were used. We found no statistically significant difference in height growth between the 2-, 3-, and 4-foot tubes. Out of the 63 sites sampled 15 sites used 2-foot tubes, 32 sites used 4-foot tubes, and 13 sites used 3-foot tubes. From an economic viewpoint, it may be just as effective for survival to use the cheaper 2-foot tubes rather than the more expensive 4 foot tubes. As only three examples were found where no tubes were used comparison of tubes with no-tubes were not appropriate. Therefore, it is unknown how effective this type of planting method may be in the Piedmont or Ridge and Valley, but it may provide for an interesting study in these two regions. Stuhlinger and others (2007) found that three different types of 4-foot tubes provided no effect on overall seedling survival of green ash or cherrybark oak, but unsheltered trees had stunted growth due to deer browse.

When available, additional parameter data were collected and this data is displayed in table 4. Interestingly, very few sites had any type of site preparation activities conducted to better prepare the site for planting. It is suspected that mowing would be the more common site preparation technique due to the availability of mowing equipment at the planting sites and the complications of using herbicides near open waters. The Coastal Plain did have the highest (12.5 percent) amount of site preparation conducted with herbicide application, while the Piedmont had the highest (8.7 percent) amount of site preparation done by mowing. Only 4 of the 16 sites in the Coastal Plain had fencing present, each being in good condition. Only 2 of the 23 sites in the Piedmont and 3 of the 24 sites in the Ridge and Valley did not have fencing present during the study. Out of the 63 sites sampled, 6 had livestock inside the planting area and caused devastating damage to the site. Some routine mowing maintenance was conducted on various sites and, as indicated in table 5, nearly 50 percent of the sites in the Ridge and Valley were mowed to control vegetative competition. This maintenance could potentially improve the growth of the planted seedlings. However, mowing grass in filter strips may decrease the sediment trapping.

Damaging factors that would alter or inhibit growth tree growth were noted (table 5). These damaging agents affected not all trees in the study, but multiple damaging agents also affected trees. The most common damaging agents involved the planting aids. The highest occurring issue for Coastal Plains and the Ridge and Valley was the tube being knocked down on the ground providing no protection to the seedling from animal consumption, human influences, or insect damage. In the Coastal Plain, 40.1 percent of the damages were due to the tube being down on the ground while missing tubes made up 25 percent and bent tubes made up 18.7 percent of the affected seedlings. Missing tubes made up the largest percent of issues in the Piedmont with 32.4 percent of the plantings missing tubes, while 19 percent of the plantings involved bent tubes. Only 17.1 percent of the plantings in the Piedmont had tubes down on the ground. The Ridge and Valley had 30.5 percent of plantings with the tubes down on the ground and 29.5 percent with missing tubes. Deer browse, though relatively low in the Coastal Plain (9.4 percent) and Piedmont (11.4 percent) made up the third highest damaging agent in the Ridge and Valley (16.7 percent). The use of 2 foot tubes in the Ridge and Valley, placing the plant at deer height for consumption may have been a contributing factor, but the data cannot support this conclusion. Overall planting aid issues comprised 83.8 percent of the problems in the Coastal Plain, 77.1 percent in the Piedmont, and 74.25 percent in the Ridge and Valley. These issues were followed closely by animal and insect damages comprising 12.5, 20, and 23.8 percent of the problems for each region respectively. Human influences including herbicide over-spray and mowed tubes only accounted for about 8 percent of the total damages in all three of the regions combined. Vegetative influences entailing overtopping vegetation had the least percent of damage on only the Piedmont and Ridge and Valley regions amounting to a mere 3.3 percent.

SUMMARY

Restoration of riparian forest vegetation via plantings is generally successful in situations having a combination of good fencing, proper species selection, and the proper installation of planting aids. The Coastal Plain and Piedmont efforts are working primarily due to the fencing out of livestock and the abundance of volunteer growth. Efforts in the Ridge and Valley need to be focused more on the control of invasive species so the desired vegetative cover is achieved. In order for these restorations to work effectively, clearly defined objectives need to be set forth for the administration of these plantings. If the improvement of water quality is the main objective of this restoration effort, then a combination of both hardwood and softwood species would likely be more effective than the use of soft mast species. The oaks used on these CREP sites are slow growing and will provide for a future stand in the long run. For the short-term, faster growing species could be selected to provide a rapid site establishment and better initial water quality improvement. Proper species selection should involve the evaluation of natural vegetation on the site and the species then selected from that composition. A combination of both

Table 5—Damaging agents with their percent occurrences ranked in each physiographic region

	Coastal Plain		Piedmont		Ridge and Valley	
Damaging agents	Percent	Rank	Percent	Rank	Percent	Rank
Deer browsed	9.4	4	11.4	4	16.7	3
Groundhog hole at base	—	—	—	—	0.95	8
Herbicide over-sprayed	—	—	0.9	11	0.95	9
Growing outside tube	—	—	4.8	6	0.95	10
Holes pecked in tube	—	—	—	—	0.95	11
Japanese beetle damage	3.1	5	8.6	5	5.2	5
Mat missing	—	—	2.8	7	—	—
Overtopping vegetation	—	—	1.9	8	1.4	6
Tube bent	18.7	3	19.0	2	11.9	4
Tube damaged	—	—	1.0	10	1.4	7
Tube down on ground	40.1	1	17.1	3	30.5	1
Tube missing	25	2	32.4	1	29.5	2
Tube mowed	3.1	6	1.9	9	.95	12

slow and fast growing species may provide for the best stand establishment.

Planting shelters are contributing to the growth and survival of these plantings, however, the data indicate that the less expensive 2 foot tubes may be just as effective as the 3- and 4-foot tubes, although the deer browse issue is site dependent. Having had few sites with site preparation techniques applied, it may be appropriate to look more closely into better site preparation techniques to more sufficiently establish the initial seedlings' growth. The majority of the damaging issues involved the planting shelters affecting the seedling's growth. In order to address these problems, some amount of inspection and maintenance should be conducted on the planted sites. Landowners and/or agency officials should routinely observe the plantings to confirm that the survival and stocking is adequate and the fencing is keeping the livestock out. Finally, better performance may be achieved through landowner education by the designated agencies and officials.

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THE USE OF GIBBERELLIC ACID AS A PRESOWING TREATMENT FOR CHERRYBARK AND NUTTALL OAK ACORNS

John C. Adams, Joshua P. Adams, and R.A. Williams[1]

Abstract—The use of gibberellic acid to enhance growth and development in plants has been shown in many species. Gibberellic acid is a naturally occurring hormone that can, in certain concentrations, affect dormancy, flowering, fruit set, growth, frost protection, root formation, and other growth processes. The positive effect on germination by this hormone treatment could help the nurseryman produce more uniform seedling germination and a higher germination value. Cherrybark (*Quercus pagoda* Rafinesque) and Nuttall (*Q. nuttalli* Buckley) oaks were chosen to evaluate seed treatment with gibberellic acid to enhance germination treatment. Three treatments and a control were used to treat the seed which were then planted in a greenhouse study with a 2 by 2 factorial with five observations in each species/treatment. Germination of the seedlings was monitored for 31 days and seedling germination times were recorded. Analysis of the effectiveness of the treatments was done using Czabator's germination value index. The use of the Czabator's gibberellic acid had a positive effect on both cherrybark and Nuttall oak. The cherrybark species responded significantly to the higher levels of the gibberellic acid indicating that the use of the hormone could be a useful tool in enhancing germination which may be important when seeds are in short supply.

INTRODUCTION

The use of gibberellic acid to enhance performance of certain plant growth attributes has been shown in numerous species ranging from monocots such as rice (Durand 1993) to dicots such as oak (Vogt 1970). Gibberellic acid is a strong, naturally occurring plant hormone and can influence flowering, dormancy, fruiting, growth, etc. (Riley 1987). Vogt (1970) found that northern red oak (*Quercus rubra*) had a positive response reducing the time to 50 percent germination from seven weeks to three weeks when treated with GA3. Farmer (1974) reported similar GA influenced results with northern red oak. Bonner (1976) working with cherrybark oak (*Q. pagoda*) noted enhanced germination when gibberellic acid soak was used. Singh reported that spruce seeds germinated better than silver fir when both species were treated with GA3. Rawat (2006) reported that germination of three species (*Abies pindrow, Cxupressus torulosa, and Picea smithiana*) was increased by a combination of GA3 and presoak temperatures. This increase in germination increased the available seedlings by increasing the total seedlings obtained from a lot of seed.

The germination and initial growth of oak seed especially cherrybark and Nuttall (*Q. nuttallii*) was of special interest in the Southern and Mid-South states because of the value of the cherrybark and the demand for the Nuttall oak in the aforestation effort in the Mississippi River floodplain. In some years, seed of both of these species are in short supply because of poor seed crops; any technique that would enhance the germination both in speed and completeness was of interest.

METHODS AND PROCEDURES

A group of cherrybark and Nuttall oak acorns was made from randomly selected trees of each species located in north LA. The seed was float tested and a random sample of 250 seeds per species was selected for use in this study. The seed were stratified in cold (35 °F), moist conditions from collections in November until the study began in the greenhouse in March.

Four treatments were applied to the seed. They were Gibberellic acid (GA3) in concentrations of 100, 200, 300 ppm GA3 and distilled water. Seed were removed from stratification and the seed were dried for 24 hours. The seed were placed in the appropriate treatment solution and soaked for 24 hours. Root-trainer seedling containers were filled with pro mix soil media and the seed were then placed approximately 1/2 inch under the surface of the soil media. Greenhouse temperatures were 80 °F daytime and 68 °F nighttime and the containers were watered when needed.

Two-hundred-fifty seed per treatment were placed in 50-seed groups for a total of 1,000 seeds in the study. After the first germinating oak was recorded, the planting was evaluated every 3 days until the study was terminated 30 days later. In each observation period, the number of germinants was recorded by day to get the cumulative germination value.

The evaluation of the effectiveness of the treatments was done by using a germination value calculated by using Czabator's (1962) formula (GV=PV X MDG), which combines the mean daily germination (MDG) and a peak value (PV), which combines both speed and completeness of germination. A germination curve plotting cumulative germination on a graph with a y=number of germinants and the x=the days in the test, was used by Czabator to determine the peak values. In this study, the PV was determined mathematically and used in the formula to determine the germinative value. The germinative value was then analyzed using both analysis of variance produced by PROC GLM (SAS 1995), and Duncan's multiple range test to separate the means. The study design was a 2 by 2

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factorial with five observations in each species by treatment combination.

RESULTS AND DISCUSSION

Analysis of variance indicates that there were no differences between the germination values of the treated Nuttall oak. There were significant differences in the germination values of the germination values of cherrybark oak (table 1). Duncan's Multiple Range Test indicates that for cherrybark oak the 300 ppm GA3 soak was effective and the germative value was significant (table 2). Only in the highest levels of treatment did a positive result occur indicating that for these two oak species there needs to be more work done to determine the level for the optimum response. In cherrybark oak, the threshold may have been reached with the 300 ppm level but either the strength of the treatment solution or the time of the soaking needs to be tweaked. The Nuttall oak had not reached a response level at the solutions that were used in this study, and again, the solution level and the length of treatment need to be evaluated in additional studies. If the effective treatments can be worked out for these and other oak species, better utilization of the seed collected in short seed years may be accomplished and the nurseryman will have another tool for seedling production.

Table 1—Composition of expected mean squares (EMS) variances and results for analysis of variation of germination value where both species and treatment are fixed effects

Source of Variation:	Expected Mean Squares	Mean Squares	F-value
Species (S)	$\sigma_e + tn\sigma_s$	13.67	< 0.0001
Treatment (T)	$\sigma_e + sn\sigma_t$	1.62	0.03
S*T	$\sigma_e + n\sigma_{st}$	2.26	0.01
Error	σ_e	0.46	

Table 2—Cherrybark and Nuttall oak by species by treatment germination value (GV) means

Species	Treatment (ppm)	Mean GV	Duncan Grouping
Cherrybark Oak	300	2.80	A
Cherrybark Oak	100	1.55	B
Cherrybark Oak	200	1.10	BC
Cherrybark Oak	Control	0.83	BC
Nuttal Oak	200	0.56	BC
Nuttal Oak	Control	0.38	C
Nuttal Oak	100	0.37	C
Nuttal Oak	300	0.29	C

Means followed by the same letter are not significant at the P < 0.05 probability.

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RELEASING RED OAK REPRODUCTION USING A GROWING SEASON APPLICATION OF OUST

Jamie L. Schuler and John Stephens[1]

Abstract—In most cases, newly harvested upland oak stands contain sufficient numbers of red oak stems to form a fully stocked oak stand in the future. Unfortunately, many stands will not reach full stocking of oak due to intense competition from other non-oak reproduction. There are few feasible options to release established oak reproduction from other broadleaf woody or non-woody vegetation. This study assessed the year 1 results of an over-the-top application of the herbicide Oust (0.2 kg/ha) during the growing season to reduce the competitiveness of non-oak species. The first year after treatment, Oust reduced the total height and diameter of non-oak species by about 20 percent without affecting mortality or growth of red oak stems. The application of Oust over the top of actively growing mixed oak stand, while not a labeled use, does show promise as an effective and operationally feasible release treatment.

INTRODUCTION

The intent of this work is to explore an efficient means to effectively enhance the survival and productivity of red oak (*Quercus rubra* L. and *Q. velutina* Lam.) reproduction on moderately productive cutover stands in the Ozark highlands. Following harvesting, a substantial decrease of red oak composition has been noted in stands that previously supported large numbers of mature oak stems. Regeneration failures from the standpoint of oak stems have resulted from their slow growth and poor survival during the first decade relative to species like red maple and black cherry but typically not from a lack of new germinants. Most stands have several thousand oak seedlings per ha following harvest (Kays and others 1988). However, even 2,200 to 9,900 oak stems/ ha have been reported inadequate because most seedlings were too small to compete with other woody and herbaceous species (Arend and Scholz 1969). Current recommendations for naturally regenerating red oak species on good sites are based on the paradigm that several hundred large stems (>1.2 m tall) of advance regeneration are needed before the overstory should be harvested (Johnson and others 2002).

The recent oak decline in northern Arkansas, facilitated in part by a red oak borer (*Enaphalodes rufulus* Haldeman) epidemic, has resulted in stands with significant mortality to mature red oak growing stock. This decline has led to many stands being salvage logged without any consideration as to whether stand conditions were favorable (i.e., adequate numbers of large oak advance reproduction) to regenerate a new stand that will have a significant component of red oak species. Subsequent post-harvest inventories show that the canopy gaps produced by individual tree mortality and salvage operations have regenerated new cohorts of seedlings that are dominated by less desirable dogwood (*Cornus florida* L.), blackgum (*Nyssa sylvatica* Marsh.), and black cherry (*Prunus serotina* Ehrh.) stems that are at a competitive advantage over the initially slow growing northern red oak (Heitzman 2003). Without the large advance regeneration purportedly required for maintaining the red oak composition present prior to the oak declines beginning in 1999, these new stands will have significant reductions in their future oak component. New techniques are needed to reverse these undesirable stand conditions that fell outside of the current regeneration requirements for red oak stands.

Large growth responses to vegetation control treatments that release newly regenerated oak stems from both woody and herbaceous competition are possible (Schuler and Robison 2006). However, the issue that has plagued natural and plantation hardwood forest management has been the lack of species-specific herbicides, such as those readily available for pines (e.g., imazapyr) (Schuler and others 2004). Thus far, these hardwood-specific herbicides are only labeled for a few plantation-grown species such as sweetgum (*Liquidambar styraciflua* L.) and cottonwood (*Populus deltoides* Bartr. ex Marsh.).

Oust is typically used as a pre-emergent herbicide in loblolly pine (*Pinus taeda* L.) stands and over dormant hardwood stems. Herbicide screening trails have identified red oak resistance to post-emergent, over-the-top applications of Oust during the summer growing season (Ezell and Nelson 2001). Other studies have shown that similar applications of Oust were toxic to species like black cherry, white ash (*Fraxinus americana* L.), and many herbaceous species when applied for fern control in natural regeneration in PA (Horsley and others 1992). The focus of this study was to determine whether Oust applied over-the-top of red oak reproduction during the growing season can kill or severely reduce the competitiveness of competing vegetation (other hardwood stems), while still affording red oak tolerance.

METHODS

This study was conducted on an upland mixed oak stand in Independence County, AR that was partially harvested three years prior to treatment. Eight treatment plots were delineated in areas with large canopy gaps that facilitated abundant reproduction. Treatment plots measured 6.1 by 12.2 m. Two treatments were randomly assigned to four untreated control plots and four treated plots that received 0.2 kg/ha of Oust XP applied as a broadcast spray from a 1.8-m boom during May 2006.

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On each treatment plot, 20 to 30 red oak stems were individually tagged, and groundline diameter and total height were recorded. Through the center of each treatment plot, a 2.4 by 12.2 m measurement strip was delineated and permanently monumented for the purposes of quantifying oak seedlings and non-oak woody stems. Total heights of all stems within the center strip were tallied by species, including the individually tagged red oak stems. Individual oak and non-oak stems within the measurement strip were inventoried immediately prior to the application of treatments and again at the end of the first growing season (fall 2006) following the application of treatments.

Oak and non-oak species were compared by treatment and measurement period. Analysis of variance was used to detect significant differences at alpha =0.10.

RESULTS AND DISCUSSION

The goal of this study was to assess the ability of Oust to reduce the competitive status of non-oak stems without affecting the growth and survival of red oak seedlings. One growing season after treatment, non-oak stems treated with Oust had 30 cm shorter total heights compared to untreated stems (P=0.066) (table 1). Stem density changed markedly by the end of the first growing season. Oust treated plots had 22 percent fewer stems by the end of the growing season, while stem density was reduced by 7 percent on the untreated plots. However, differences in stem density between control and Oust treatments and between beginning and the end of year measurements within each treatment were not significant (P>0.10).

The non-oak group included numerous species. Certain species are known to be more sensitive to Oust than others. Horsley and others (1992) demonstrated that black cherry and white ash were killed or severely impacted by early summer applications of 0.13 kg/ha of Oust, whereas established red maple were essentially tolerant. For this study, treated and untreated plots had few differences in relative species composition within each treatment (table 2). Only redbud (P=0.097) and the miscellaneous group (P=0.098) for the control treatment showed significant changes from the beginning of the experiment to the end of the first growing season. However, the power to detect statistical differences was limited due to low representation within many species/ species groups.

For total height, no statistical differences were detected between control and Oust treated stems at the initiation of the study (table 3). By the end of the first year, differences between treatments for various species were beginning to emerge. For example, stem height of elm species group was 30 percent lower than on untreated controls (P=0.024) (table 3). Sweetgum heights were also significantly lower on the Oust treated plots compared to the untreated controls (P=0.086), but these were comparing only a few stems per treatment (table 2).

Red oak stems on both treatments had minimal mortality. At the rate applied, a May application of Oust does not cause death to established stems. Mortality ranged from three to four percent for untreated and treated stems. This result was corroborated by studies in naturally regenerated hardwood stands in PA (Horsley and others 1992) and planted stands in MS (Ezell and Nelson 2001).

After one year, no significant differences were detected for red oak height or diameter between treatments (table 4). While not significant, trends did show red oaks having larger increases in height and diameter growth on Oust treated plots versus the control plots. When red oak stems were separated into <100, 101 to 200, and 201 to 300 cm height classes, groundline diameter for the smallest size class improved by 34 percent on the Oust treated plots (P=0.082, fig. 1). No other significant differences were noted among the other size classes for height (fig. 2) or diameter. The lack of notable differences after one growing season is not unexpected. Relative to many intolerant species, red oaks have a much more conservative growth strategy. Responses to release, especially on younger stems, may take several years to develop (Schuler and Robison 2006).

CONCLUSIONS

Despite our best silviculture there will always be instances where ameliorative treatments are needed. Regeneration is a process somewhat controlled by chance. While there are ways to improve the probability of success, failures do occur, especially if one is interested in particular species. For this study, an unforeseeable pest outbreak resulted in a stand being regenerated without any attempt to control species composition, leaving red oak reproduction at a competitive disadvantage. Few, if any, cost-effective release treatments are available for oak seedlings and saplings. The use of Oust to release oak species from both woody and non-woody competition does appear to have promise. Some non-oak species had reduced stem densities and reduced growth compared to untreated plots. Mortality of treated red oak stems was equivalent to the untreated stems, which was almost nonexistent. The red oak stems treated with Oust will have to be monitored over several years to determine whether Oust can be considered a positive treatment for releasing established reproduction, but the trends indicate

Table 1—The response of non-oak species to a single growing season application of Oust

Treatment	Initial height (cm)	Year 1 height (cm)	Initial stems/ ha	Year 1 stems/ acre
Control	122.7	156.2*	14,126	13,119
Oust	107.7	126.1	16,482	12,782

* = A significant difference (alpha=0.10) between treatments .

Table 2—Species composition of non-oak species (percent of total) prior to the initiation of treatments (May 2006) and at the end of the first growing season (fall 2006)

		Control		Oust	
Common name	Scientific name	Pre-treatment	Year 1	Pre-treatment	Year 1
white ash	*Fraxinus americana*	26.9	27.3	27.3	17.6
black cherry	*Prunus serotina*	8.5	7.0	2.2	0.8
French-mulberry	*Callicarpa americana*	4.6	7.0	0.0	0.0
red buckeye	*Aesculus pavia*	8.5	8.9	4.4	6.3
elm	*Ulmus* spp.	10.2	8.1	31.4	31.3
hackberry	*Celtis occidentalis*	10.9	4.1	3.6	3.6
hickory	*Carya* spp.	10.4	8.0	3.2	4.9
eastern redcedar	*Juniperus virginiana*	6.5	7.9	4.0	5.0
persimmon	*Diospyros virginiana*	0.0	4.5	4.5	7.8
privet	*Ligustrum* sp.	3.5	1.6	0.0	0.5
redbud	*Cercis Canadensis*	6.4*	0.8	2.5	1.5
red maple	*Acer rubrum*	0.8	2.5	0.0	0.8
sweetgum	*Liquidambar styraciflua*	0.0	1.8	4.8	5.9
miscellaneous		2.8*	11.5	12.2	14.1

Columns may not add to exactly 100 percent due to rounding.
* = significant difference (alpha=0.10) between measurement periods within species and treatment.

Table 3—Mean total stem height (cm) for various species

	Pre-treatment		Year 1	
Species/ species group	Control	Oust	Control	Oust
white ash	121.0	93.2	124.0	141.1
black cherry	134.2	178.0	143.7	152.0
red buckeye	105.2	114.1	132.7	112.8
elm	105.4	114.8	191.2*	134.0
hackberry	132.5	124.1	154.3	138.3
hickory	124.1	114.1	167.8	116.4
eastern redcedar	144.3	99.9	162.0	109.0
persimmon	-	213.7	256.9	202.6
redbud	95.0	118.1	168.0	90.3
red maple	152.5	-	174.3	135.0
sweetgum	-	70.3	258.0*	85.7

* = A significant treatment difference (alpha=0.10) within a measurement period.

Table 4—The response of red oak stems to a single growing season application of Oust

Treat-ment	Initial height (cm)	Year 1 height (cm)	Initial diameter (mm)	Year 1 diameter (mm)
Control	136.1	151.7	13.1	17.9
Oust	142.7	161.0	14.7	20.9

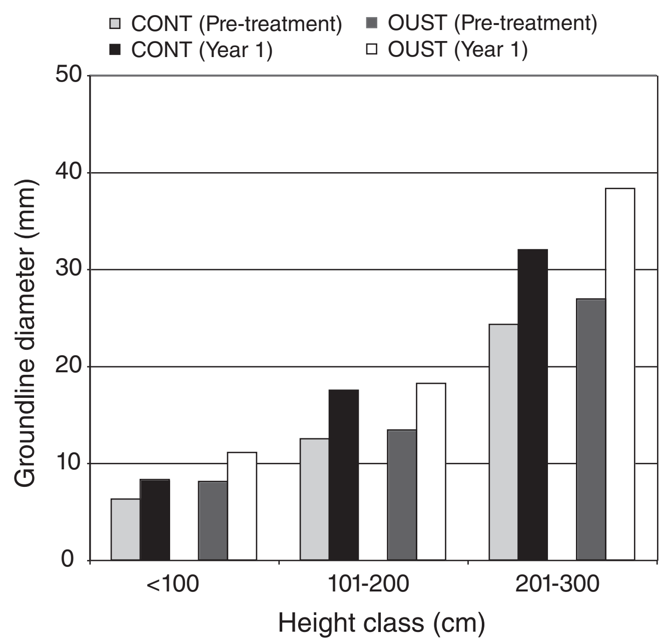

Figure 1—Diameter growth of various size classes of red oak seedlings treated with a growing season application of Oust.

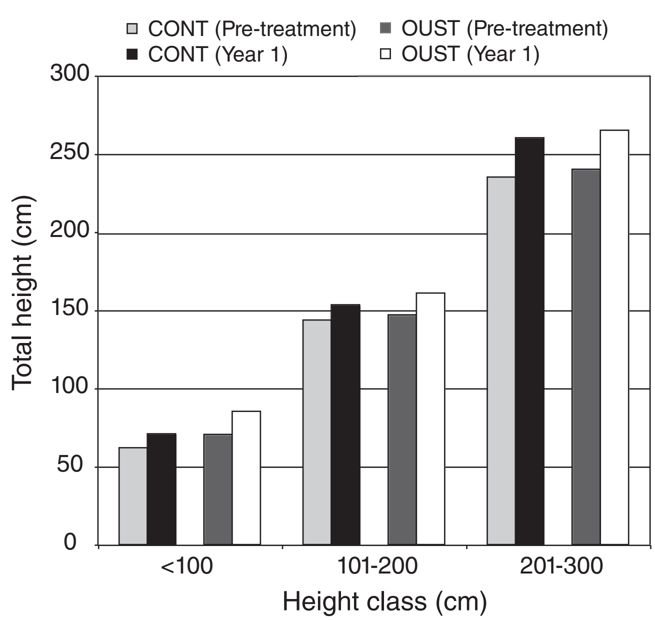

Figure 2—Height growth of various size classes of red oak seedlings treated with a growing season application of Oust.

that 0.2 kg/ha of Oust XP is effective. The current limitation of this treatment is that Oust is not labeled for a growing season release of naturally regenerated hardwood seedlings.

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SILVICULTURAL AND LOGISTICAL CONSIDERATIONS ASSOCIATED WITH THE PENDING REINTRODUCTION OF AMERICAN CHESTNUT

Douglass F. Jacobs[1]

Abstract—Traditional breeding for blight resistance has led to the potential to restore American chestnut (*Castanea dentata* (Marsh.) Borkh.) to Eastern United States forests using a blight resistant hybrid chestnut tree. With prospects of pending wide-scale reintroduction, restoration strategies based on ecological and biological characteristics of the species are needed. American chestnut was adapted to a relatively wide range of site conditions, has the ability to persist under shaded environments yet respond quickly to release, and exhibits rapid growth and competitive ability. These characteristics are discussed in reference to potential for hybrid chestnut regeneration to spread into adjacent forest stands. The use of a hybrid for American chestnut reintroduction may prompt a variety of ecological concerns. Additionally, it is likely that many hybrid chestnut plantings will result in introduction of hybrid chestnut to areas outside its original range. Limitations in genetic fitness, potential for mutation of the blight pathogen, and threats from other exotic pests and pathogens will serve as continual barriers to chestnut restoration.

INTRODUCTION

American chestnut (*Castanea dentata* (Marsh.) Borkh.) was once a dominant tree species in the forests of Eastern North America, though the species was essentially eliminated as a canopy tree following the introduction of the chestnut blight fungus, *Cryphonectria parasitica* (Murr.) Barr. A dedicated breeding program, sponsored in large part by the American Chestnut Foundation, has made rapid progress toward producing a blight-resistant hybrid chestnut tree for restoration. This hybrid tree with be approximately 94 percent American chestnut and 6 percent Chinese chestnut (*Castanea mollissima* Blume), and is expected to be nearly indistinguishable from the American chestnut tree (Hebard 2006). With increasing optimism toward initiating a large-scale reintroduction program in the foreseeable future, it is important to address additional considerations unrelated to the blight resistance breeding program. This paper summarizes issues presented in much greater detail in Jacobs (2007).

ECOLOGY AND SILVICS OF AMERICAN CHESTNUT

Because chestnut blight has been prevalent since the early 1900s, relatively little is known about the biological and ecological attributes of American chestnut compared to other common forest tree species. There has been a recent movement, however, toward enhancing this knowledge through new experimental studies as well as examination of historical patterns of occurrence. American chestnut was often found in high abundance on upland habitats composed of non-calcareous, acidic to moderately acidic, and moist but well-drained sandy soils (Abrams and Ruffner 1995, Russell 1987, Stephenson and others 1991). It was formerly assumed that American chestnut occurred infrequently in ravines or valleys, but a recent survey reported that the species occupied 25 to 40 percent of the basal area in pre-blight stands of sites sampled in riparian zones in the southern Appalachians (Vandermast and Van Lear 2002). This suggests that American chestnut was adapted to a relatively wide range of site conditions.

American chestnut responds positively to high light conditions compared with co-occurring species (Latham 1992, King 2003). The species can apparently survive, however, for extended durations under shade (Latham 1992, McCament and McCarthy 2005, Paillet and Rutter 1989) and respond vigorously following release through disturbances that create canopy gaps (McEwan and others 2006, Paillet 2002, Paillet and Rutter 1989). This evidence suggests that American chestnut is an intermediate to tolerant species with regard to ability to survive under prolonged shading (McCament and McCarthy 2005, Wang and others 2006).

With regard to growth rates, historical literature suggested that American chestnut is highly competitive and fast growing during early development. These contentions have been confirmed in recent years, with reports of diameter growth rates approximating 5 mm per year in plantations and natural stands, with maximum values around 10 to 12 mm per year (Jacobs and Severeid 2004, McEwan and others 2006, Paillet and Rutter 1989).

PLANTING STRATEGIES FOR AMERICAN CHESTNUT RESTORATION

Recent studies have suggested underplanting (Wang and others 2006) or thinning and burning (McCament and McCarthy 2005) for reforestation of hybrid chestnut. It is also likely that afforestation (i.e., planting in former agricultural fields or pastures) will be an important target for hybrid chestnut plantings.

It is possible that a similar sequence to that reported by Paillet and Rutter (1989) could help to promote regeneration of hybrid chestnut into adjacent forests following afforestation plantings. Under this scenario, hybrid chestnut trees would be established in afforestation plantings (fig. 1). After reaching reproductive age, seed could then be disseminated into adjacent forests and along edges where pioneer trees could become established as canopy gaps were created (fig. 2). These trees would produce more seed as they continued to develop and a large pool of advance regeneration could

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Figure 1—American chestnut afforestation planting.

eventually be released through disturbance. This would lead to dominance of hybrid chestnut in the succeeding stand (fig. 3). Because of the high capacity of American chestnut to vigorously stump sprout (fig. 4), hybrid chestnut regeneration is likely to maintain itself or increase in volume following cutting or other disturbance.

Figure 2—Establishment of American chestnut tree along forest edge.

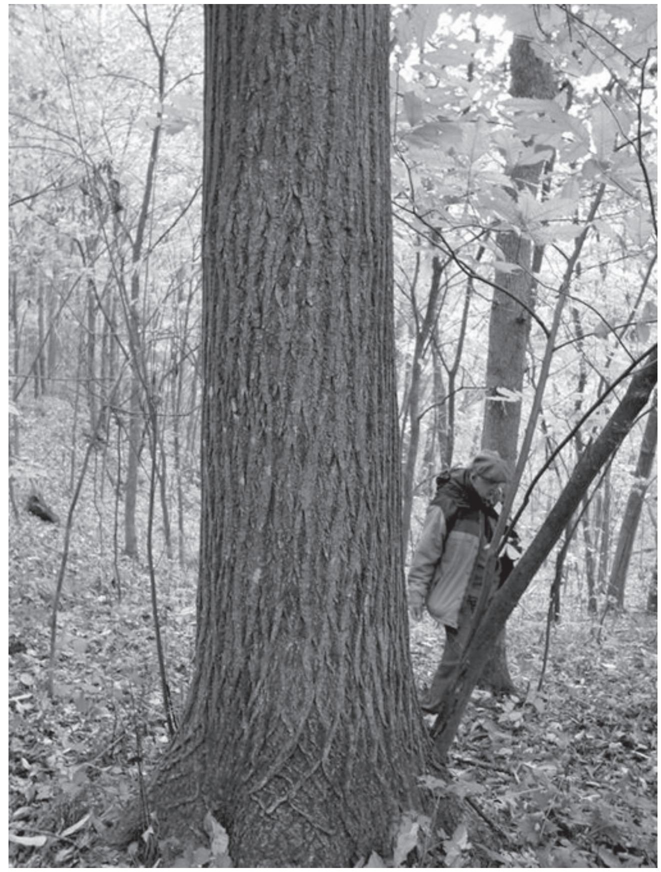

Figure 3—Large established American chestnut tree resulting from regeneration of pioneer tree.

PENDING CHALLENGES TO CHESTNUT RESTORATION

Many pending barriers to successful American chestnut restoration are likely to be encountered. Because hybrid chestnut is not pure American chestnut, some groups are likely to oppose planting these hybrid seedlings under the auspices of American chestnut restoration. This is most likely to be a factor under public land management, but could also

Figure 4—American chestnut sprouts from cut stump.

have some implications associated with governmental cost-share programs on private lands. On reforestation sites on public lands, social resistance to harvesting may limit the ability to create large canopy openings that are most likely to promote vigorous growth of planted trees.

There are also threats from various exotic insects and pathogens other than the chestnut blight fungus. *Phytophthora cinnamomi* Ronds, an introduced soilborne oomycete probably poses the greatest concern at present, and may necessitate site selection as well as further resistance breeding (Rhoades and others 2004). Other possible threats include the Oriental gall wasp (*Dryocosmus kuriphilus* Yasumatsu), Gypsy moth (*Lymantria dispar* L.), and ambrosia beetles (*Xylosandrus crassiusulus* Mot. and *X. saxeseni* Blandford).

Regarding deployment, it is likely that early hybrid chestnut restoration plantings will be limited by quantities and cost of blight-resistant seed and seedlings. Furthermore, repeated testing will be needed to verify blight resistance and American chestnut phenotype in the early hybrid sources. The long-term genetic adaptability and maintenance of genetic variation in the current hybrid sources, which use a relatively narrow range of genotypes, is another factor that will need to be critically assessed. Finally, when blight-resistant hybrid chestnut seedlings are released, it will be difficult to ensure that plantings are limited to areas representing the original American chestnut range. Many of the areas where hardwood afforestation planting programs are most active are outside of the primary American chestnut range (i.e., the Midwestern United States or the Lower Mississippi Alluvial Valley).

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Longleaf Pine

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EFFECTS OF PRESCRIBED FIRE ON VEGETATION AND FUEL LOADS IN LONGLEAF PINE STANDS IN THE BLUESTEM RANGE

James D. Haywood[1]

Abstract—Three longleaf pine (*Pinus palustris* Mill.) sites in the bluestem (*Andropogon* spp. and *Schizachyrium* spp.) range were selected in Louisiana for a 40-month study: a shelterwood, a small pole stand, and a newly planted clearcut. On each site, two treatments were applied: check and prescribed fires (PF). Prescribed fires were conducted in May 2001 and June 2003. Overstory basal area increased in the shelterwood and small-pole stand regardless of treatment. In August 2004, the checks had 39 percent and the PF plots had 15 percent cover in arborescent plants. Initially, grass cover was similar on both treatments (45 percent average), but in August 2004, grass cover was 16 percent on the checks and 28 percent on the PF plots. The decrease in grass cover was likely associated with increasing basal area in the overstory and changes in arborescent plant cover in the understory. Prescribed fire reduced dead fuel load over the 40 month period.

INTRODUCTION

Before European settlement, longleaf pine (*Pinus palustris* Mill.) forests occupied as much as 37 million ha across the Southeastern United States and constituted the most extensive ecosystem in North America (Landers and others 1995, Brockway and others 2005). Across that vast area, longleaf pine depended on natural or anthropogenic fires, because without fire, other pines and hardwoods would eventually succeed the species (Wahlenberg 1946, Haywood and others 2001, Brockway and others 2005). Extensive exploitation, as well as fire protection implemented during the 1920s and a bias against longleaf pine as a regeneration source allowed invasive hardwoods and other southern pines to replace longleaf across its natural range (Barnett 1999). By 1996, only 1.2 million ha of longleaf pine forest remained (Outcalt and Sheffield 1996).

Currently, several state and federal agencies, non-governmental organizations, and private individuals are restoring longleaf pine across the Southern United States (Brockway and others 2005). The desired future condition is a park-like longleaf pine overstory with few midstory hardwoods except in riparian and other moist areas, and a rich and diverse ground cover of herbaceous and low woody plants that can be maintained by frequent surface fires. Thus, prescribed fire is an essential ecological process in the effort to restore and maintain the longleaf pine-bluestem (*Andropogon* spp. and *Schizachyrium* spp.) range (Landers and others 1995, Barnett 1999, Haywood and others 2001, Brockway and others 2005). To develop further information on fire dynamics in such ranges in the West Gulf Coastal Plain, I studied the effects of prescribed fire on fuel load and vegetation over a 40-month period.

METHODS

Study Sites

The three study sites are within longleaf pine-bluestem ranges on the Kisatchie National Forest in central LA. Study Site 1 (block 1) is a longleaf pine shelterwood. Originally, the site was a mixed pine and hardwood stand that periodically had been prescribed burned. The loblolly pines (*P. taeda* L.) were harvested and the hardwoods were deadened in 2000 to create the shelterwood. It was underplanted with longleaf pine seedlings in November 2000 although a heavy crop of natural regeneration was present. The understory was sparse grass, low brush, and other taxa. Study Site 2 (block 2) was a recent clearcut. Originally, the site was a periodically burned loblolly pine and hardwood stand that had been harvested in 2000. It too was planted with longleaf pine seedlings in November 2000. The plant cover was a grass rough with scattered low brush. The soils at Sites 1 and 2 are Kolin and Gore silt loams, respectively. Site 3 (block 3) is a periodically burned small pole stand of longleaf pine with a grass rough understory that originated from direct seeding. The soil is a Ruston fine sandy loam.

Study Establishment and Measurements

Each of the three sites (blocks) was 10 ha in size, and each block was divided into three areas. Two areas within each block were randomly selected to receive prescribed fire conducted in May 2001 and June 2003. The third area was the check, which received no fire or other disturbance during the study. Within each of the three areas, a 0.10-ha plot was established for making fuel and vegetation measurements. In April 2003, overstory trees (stems > 10-cm d.b.h.) were inventoried and diameter at breast height (d.b.h.) measured on Blocks 1 and 3; total height and d.b.h. of overstory trees were measured again in February 2005. Using the 2005 measurements, I calculated volume per tree with Baldwin and Saucier's (1983) formulas for longleaf pine.

Four 10-m^2 subplots were randomly selected and established within each main plot. In August 2004, all understory trees and shrubs over 1.4 m tall with a d.b.h. less than 25 mm were inventoried on the 10 m^2 subplots, and d.b.h. was measured. Initially, I attempted to study midstory vegetation changes using the 10-m^2 subplots; however, the midstory trees were too scattered, nullifying this plan.

A 1-m^2 subplot was randomly nested within each 10-m^2 subplot; therein, percentage of cover was estimated for plants no taller than 1.4 m. These cover estimates were made to the nearest percent for nine taxa—trees, shrubs, blackberry (*Rubus* spp.), ferns, forbs, grasses, grass-likes, legumes, and woody vines—during July 2001, June 2003, July 2003, and August 2004.

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Fuel load was measured on four randomly established 2 by 5 m fuel-sample plots within each 0.10-ha main plot and the fuel-sample plots were distinct from the subplots used to inventory vegetation. Each fuel-sample plot was divided into ten 1-m^2 subplots. On each sample date, a 1-m^2 subplot was randomly selected for sampling fuel load without replacement. Fuel samples were collected before and 6 weeks after each prescribed fire on all three treatments. The sampled fuels were separated into five fuel classes considered available for burning based on Deeming and others (1977) fire-danger-rating system. The five fuel classes were as follows: (1) living foliage of all plants within 2 m of the ground; (2) living blackberry canes, woody stems, and vines no more than 6 mm in diameter within 2 m of the ground; (3) 1 hour time-lag dead fuels (surface litter and duff to a 0 to 6 mm depth and small roundwood and stubble no more than 6 mm in diameter); (4) 10-hour time-lag dead fuels (litter from a 6 to 25 mm depth and roundwood and stubble between 6 and 25 mm in diameter); and (5) 100 hour time-lag dead fuels (litter from a 25 mm to 100 mm depth and roundwood between 26 and 75 mm in diameter). In addition, in the post burn samples, two additional fuel classes were collected—(6) needlecast after the fire and (7) regrowth of vegetation—to keep these classes from biasing how much fuel had been consumed in the fires. Sampled fuels were dried at 80 °C for 72 h in a forced-air oven and weighed. The differences in pre-burn and post burn fuel samples (not including needlecast or regrowth following the burn) were used with a best estimate of rate-of-spread to calculate Byram's fire intensity on the prescribed fire (PF) plots as described by Haywood (1995).

Prescribed burning was conducted by strip headfiring the treatment areas once baseline backfires had been established. Overall, the prescribed fires in 2001 averaged 211 kJ/s/m (table 1), which was 22 percent higher than the 173 kJ/s/m intensity recommended as a maximum for prescribed fires (Deeming and others 1977). Average fire intensity was 467 kJ/s/m in 2003. Although above recommended levels, the fire intensities in both years were not greater than fire intensities reported in other longleaf pine-bluestem ranges (Haywood 2002).

Data Analysis

The statistician reviewing this paper suspected that there were site-by-treatment interactions, which nullified the block effect and would leave no degrees of freedom for Error Mean Squares in the analyses. Therefore, I do not present statistical results, although I will discuss trends in the data based on prior, albeit inappropriate, analyses. In those earlier analyses, I compared overstory stocking and basal area measurements in April 2001 and February 2005 and volume per ha in 2005. In August 2004, I also compared number of stems and basal area per ha and average d.b.h. of understory trees and shrubs greater than 1.4 m tall with a d.b.h. less than 25 mm. Percent cover of understory vegetation was compared on the following dates: post-burn in June 2001, preburn in June 2003, post-burn in July 2003, and post-burn in August 2004. For the percent cover comparisons, I grouped cover into three taxa–arborescent vegetation (trees, shrubs, and blackberry), grasses, and others (ferns, forbs, grass-likes, legumes, and woody vines).

For fuel loads, the ovendried mass of live stems and foliage both followed the same pattern of treatment response throughout the study; and so, the two classes of live fuels were combined. Thereafter, live fuels, 1-hour time-lag dead fuels, 10-hour time-lag dead fuels, and 100-hour time-lag dead fuels were compared in May and June 2001, June and July 2003, and August 2004.

Table 1—Fire intensities by site and time of burning

Sites	May 2001	June 2003
	(kJ/s/m)	*(kJ/s/m)*
Shelterwood	1	531
Small pole stand	426	544
Clearcut	206	327

RESULTS

Overstory Vegetation

Number of overstory trees per ha did not change much from April 2001 to February 2005 on the shelterwood. Across both treatments, the average number of trees increased in the small pole stand from 163 to 595 trees/ha because of ingrowth over this period (table 2). Average basal area/ha increased during this period from 7 m^2/ha to 8 m^2/ha in the shelterwood stand and from 1.4 m^2/ha to 7.2 m^2/ha in the small pole stand. In 2005, total volume of longleaf pine was 74 m^3/ha in the shelterwood stand and 35 m^3/ha in the small pole stand with little differences between the check and PF plots.

Understory Vegetation

After the first prescribed fire, percent cover of understory vegetation had been little affected by burning. For the check and PF treatments, cover of all plants totaled 95 and 91 percent, respectively. Following the second fire, the PF treatment had less grass and arborescent plant cover than the checks, averaging 41 and 21 percent on the checks and 26 and 4 percent on the PF plots, respectively (fig. 1). The shift in arborescent plant cover after the second prescribed fire was still evident in August 2004. Grass cover did not return to preburn percentages by August 2004 on either treatment, and grass cover was less on the check than PF plots at that date. Initially on the checks, grasses dominated

Table 2—Number of overstory trees and basal area per hectare

Stands/ treatments	April 2001 Stocking	April 2001 Basal area	February 2005 Stocking	February 2005 Basal area
	(trees/ha)	*(m^2/ha)*	*(trees/ha)*	*(m^2/ha)*
Shelterwood				
Check	60	9.8	60	10.6
PF*	50	4.3	50	4.9
Small Poles				
Check	140	1.2	630	7.6
PF	185	1.6	560	6.8

* PF-prescribed fire was applied in May 2001 and June 2003.

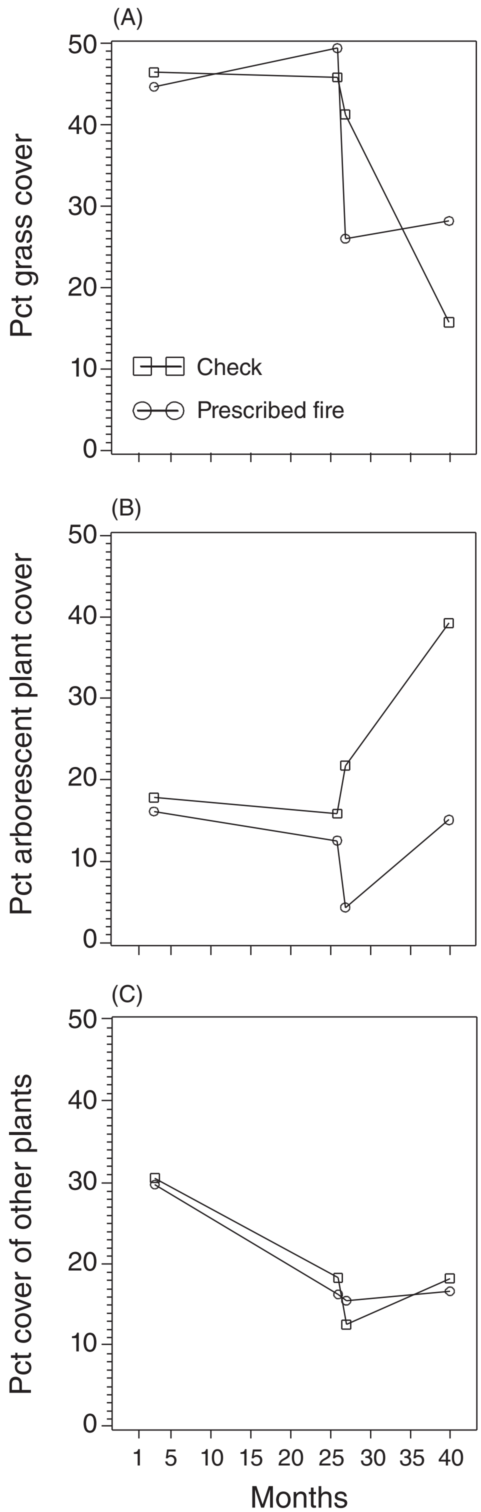

Figure 1—Percent cover of grasses (A), arborescent plants no more than 1.4 m tall (B), and other plants--ferns, forbs, grass-likes, legumes, and woody vines (C), which were measured post burn in June 2001, preburn in June 2003, post burn in July 2003, and post burn in August 2004.

the cover, but by August 2004, arborescent plants dominated the cover. On the PF plots, grasses still covered more area than the arborescent plants at the end of the study. Cover of the other understory plants decreased throughout the study, and was similar between the check and PF plots on each measurement date.

In August 2004, the PF plots had fewer and smaller understory trees and shrubs than the checks (table 3). However, there were no large differences in stocking and average diameter between treatments. Basal area combines the effects on stocking and d.b.h. into one variable. Differences in basal area between the check and PF treatments suggested that prescribed burning might be reducing understory tree and shrub cover.

Fuel Loads

Before the first prescribed fire was conducted, the mass of live fuels (stems and foliage) averaged 711 kg/ha on the two treatments (fig. 2). After the first fire, mass of live fuels increased on both treatments, but the increase was greater on the checks. Before the second prescribed fire, the mass of fuels was again similar on both treatments and averaged 1 574 kg/ha. The second fire greatly reduced the mass of live fuels from 1 550 kg/ha to only 14 kg/ha, while the mass of live fuels on the checks increased from 1 600 kg/ha to 2 332 kg/ha over the next 6 weeks. In August 2004, there was again no important difference in the mass of live fuels between the two treatments, which averaged 2 722 kg/ha. Thus, despite a major short-term change in live fuels on the PF plots after the second burn, the live fuels recovered on PF plots by the end of the study.

In May 2001, the preburn mass of 1 hour time-lag dead fuels was 2 369 kg/ha on check plots and 2 657 kg/ha on PF plots (fig. 2). The first prescribed fire reduced the mass of 1 hour fuels, but there was also a decrease in 1-hour fuels on the check plots. 1-hour fuels accumulated on both treatments before the second prescribed fire to an average of 3 224 kg/ha. The second fire reduced fuels on the PF plots (488 kg/ha) compared to the checks (3 071 kg/ha). In August 2004, there was still a difference in mass of 1-hour fuels, the check and PF plots having 2 591 and 1 493 kg/ha, respectively. Over the course of the study, the checks averaged 2 728 kg/ha and PF plots averaged 1 669 kg/ha of 1-hour fuels.

In May 2001, the preburn mass of 10-hour time-lag dead fuels was 1 929 kg/ha on the check plots and 3 259 kg/ha on the PF plots (fig. 2). Following the first prescribed fire,

Table 3—Number of stems, d.b.h., and basal area per hectare of understory trees and shrubs greater than 1.4 m tall with a d.b.h. less than 25 mm in August 2004

Treatments	Stocking	dbh	Basal area
	(stems/ha)	*(mm/stem)*	*(m^2/ha)*
Check	1500	15	0.75
PF*	1250	10	0.21

* PF-prescribed fire was applied in May 2001 and June 2003.

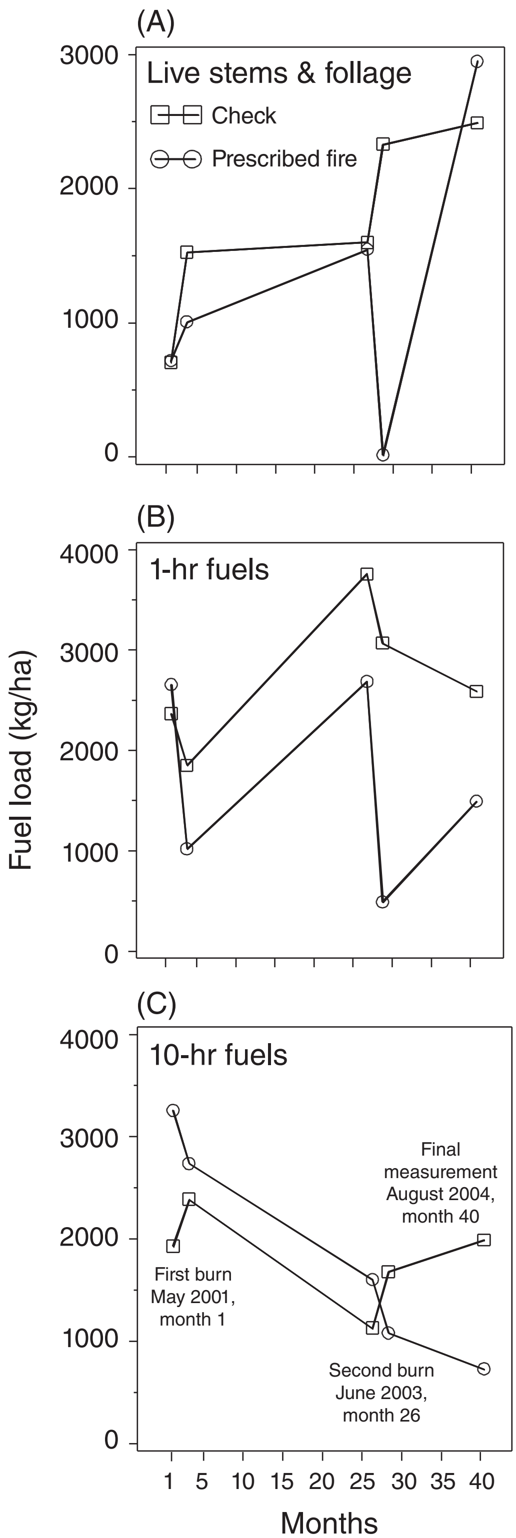

Figure 2—Fuel loads (kg/ha) for the live stems and foliage (A), 1-hr time-lag dead fuels (B), and 10-hr time-lag dead fuels (C) that were measured preburn in May 2001, post burn in June 2001, preburn in June 2003, post burn in July 2003, and post burn in August 2004.

10-hour fuels were reduced on the PF plots while increasing on the checks. In June 2003, the preburn mass of 10-hour fuels was similar on both treatments and averaged 1 365 kg/ha. Burning again reduced the mass of 10-hour fuels, while the mass of 10-hour fuels increased on the checks. In the final measurement, there was more mass of 10-hour fuels on the checks (1 990 kg/ha) than on the PF plots (727 kg/ha).

The mass of 100-hour time-lag dead fuels decreased over the course of the study. The 100-hour fuels averaged 3 701 kg/ha in May 2001 and 1 586 kg/ha in August 2004.

DISCUSSION

Prescribed fires were intense but not greater than similar fires in other longleaf pine-bluestem ranges (Haywood 2002). Fire did not change overstory composition, and basal area increased on both treatments. Prescribed fire is a way to reduce understory arborescent vegetation, remove litter, and create conditions where herbaceous productivity can increase in forest stands (Grelen and Enghardt 1973, Haywood and others 2001). However, in this study, the percent cover of grasses, ferns, forbs, grass-likes, legumes, and woody vines decreased 43 percentage points on the checks and 30 percentage points on the PF plots (fig. 1).

An increase in overstory basal area may be causing the adverse change in herbaceous plant cover (Grelen and Enghardt 1973). In the shelterwood and small pole stands, overstory basal area increased by an average of 3.6 m^2/ha on the checks and 2.9 m^2/ha on the PF plots by the end of the study (table 2). In addition, changes in understory arborescent plant cover are likely affecting herbaceous plant cover (Haywood and others 1998, Haywood and others 2001). Arborescent cover increased by 21 percentage points on the checks but decreased one percentage point on the PF plots from 2001 to 2004 (fig. 1), and at the end of the study, understory basal area was 0.75 m^2/ha on the checks and 0.21 m^2/ha on the PF treatments (table 3). Prescribed burning therefore had an immediate effect on understory arborescent vegetation as shown in figure 1. Although arborescent vegetation naturally recovers between fires (Haywood and others 2000), its coverage remained constant over the study period even as arborescent cover continued to increase on the checks. Prescribed fire kept understory arborescent vegetation under control; although no long-term visual change occurred. Controlling the cover of arborescent vegetation likely lessened its adverse effect on grass cover as seen in figure 1. Smothering of plants is also a likely factor as litter continues to accumulate on the unburned check plots (Grelen and Enghardt 1973). Regardless, it is most likely that differences in overstory and understory arborescent plant cover between treatments are reflected in differences in grass cover between treatments.

Although live fuels were reduced immediately following the second prescribed fire, they rebounded rapidly and had a net increase on the sites regardless of treatment (fig. 2). The increase in live fuels appears counter to the plant cover results (fig. 1). However, much of the live fuels were herbaceous plants that grew throughout the 2004 growing season, and increasing plant stature increases its mass without a corresponding increase in area shaded by the plant. The same is true for the arborescent plants.

The 1-hour and 10-hour time-lag dead fuels decreased on PF plots by 3 695 kg/ha while increasing on checks by 283 kg/ha over the course of the study (fig. 2). Fire apparently was reducing dead fuel loads in these longleaf pine stands.

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STAND DYNAMICS OF AN OLD-FIELD LONGLEAF PINE STAND FOLLOWING HERBICIDE APPLICATION, POOR SURVIVAL, AND SUBSEQUENT REPLANTING

E. David Dickens, Bryan C. McElvany, David J. Moorhead, Philip R. Torrance, and P. Mark Crosby[1]

Abstract—A study area in Emanuel County, GA installed to discern the effectiveness of various herbicides over newly planted (December 1999) longleaf pine (*Pinus palustris* Mill.) seedlings on an old-field site. Survival and height growth data after herbicide treatment indicate that the early (April 7, 2000) Oust+Velpar L herbicide treatment gave greater initial survival and height growth compared to nine later herbicide treatments (May 9, 2000) or an untreated control. First year survival ranged from 90 percent with the April Oust+Velpar L treatment to 40 to 63 percent with the May herbicide treatments. All dead seedlings spots that were flagged and numbered were replanted in December 2000 in the May treatments and control plots. After six growing seasons, mean longleaf survival, d.b.h., height, and green weight per acre were greater with the April application. Sixth year survival ranged from 79 percent in the April application, 53 to 67 percent for the May herbicide treatments, and 41 percent for the control. In the May treatments, originally planted trees had significantly larger heights and diameters than the replanted trees. Original planted trees had an average diameter of 3.4 inches and height of 16 feet. Replanted trees had an average diameter of 1.9 inches and height of 9 feet. During the spring of 2000, rainfall patterns were well below normal. It appears that the early April herbicide treatment allowed for the seedlings to survive this critical dry period. These results indicate that substantial longleaf establishment costs can be saved with an earlier herbicide application under severe spring drought conditions on upland well drained soils.

OBJECTIVES AND METHODS

The BASF Corporation was interested in testing various post-plant herbicides, individually and in combinations, over longleaf pine seedlings planted on an old-field site to determine herbicide effects on early survival and growth. The herbicides used were intended to control grasses and broadleaf weeds that were present on the site or expected to germinate on the site. The study area was a former 15-acre cotton field with the dominant soil being Tifton soil series (fine-loamy, well drained Plinthic Kandiudults) in Emanuel County, GA. Surface (0 to 6 inches) soil pH and available phosphorus over the study area ranged from 5.1 to 6.1 (mean of 5.5) and 29 to 83 (mean of 53) pounds per acre, respectively. Containerized longleaf seedlings were machine planted (7.25 by 12 feet spacing to achieve 500 stems per acre) in December 1999. The BASF study area was flagged off (approximately 5 acres) in early April. The operational treatment (2 ounce Oust per acre + 24 ounce Velpar L per acre) was applied on 7 April 2000 on the balance of the field. The BASF herbicide protocol treatments were applied by tractor and CO^2 sprayer at 15 gallons per acre on May 9, 2000 and are listed in table 1. The April and May herbicide treatments were applied once in a five-foot band over the top of the seedlings. The experimental design was randomized complete block with four replications per treatment and 40 (4 rows of 10) living seedlings per replication (as of May 8, 2000). All living seedlings were wire flagged, numbered, and followed initially for two years. Initial survival was tallied on 21 June 2000. First growing season survival was tallied on September 29, 2000 (table 2). Second year survival, number of seedlings out of the grass stage, and total heights were tallied on December 19, 2001. Dead seedlings were replaced in December 2000 on all May 2000 treatment plots. The statistical analysis was performed on the May treatments and the control using ANOVA and least squares means were compared using Duncan's Multiple Range Test at the 5 percent alpha level. The means tested were seedling survival, percent seedlings out of the grass stage, and height of seedlings out of the grass stage during the first two years. The best five May 2000 treatments, the control, and the April 2000 treatment plots in replications 2, 3 and 4 were re-established in March 2006 in the interior two rows. Means tested at the end of the sixth growing season (measured March 2006) were survival, d.b.h., total height, and green weight per acre (estimated from log:log equations for green weight of wood+bark by Baldwin and Saucier (1983) x fraction survival x 500 trees per acre). Rainfall patterns during 2000 from the closest weather station in Vidalia (approximately 30 miles south-southeast of the study area) were compared to the 50 year running average (fig. 1).

RESULTS

Initial longleaf seedling survival (June 21, 2000) after the banded herbicide applications ranged from 48 percent for the Arsenal at 8 ounces per acre to 74 percent for the Arsenal at 6 ounces per acre for the May treatments and 91 percent for the April Oust+Velpar L application and 62 percent for the control (table 2). There were no significant differences between the May treatments six weeks after treatment. End of the first growing season survival ranged from 40 percent for the Arsenal at 8 ounces per acre to 63 percent for the Arsenal at 6 ounces per acre for the May treatments and 90 percent for the April Oust+Velpar L treatment and 51 percent for the control (table 2). There were no significant

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Table 1—Longleaf pine herbaceous weed control trial treatments on a former cotton field in Emanuel County, GA (fine-loamy well drained Tifton soil)

	Code	Treatment[a]	Application Date
[b]	C	Control, no treatment	May 9, 2000
[b]	A4	Arsenal 4 ounces per acre	May 9, 2000
[b]	A6	Arsenal 6 ounces per acre	May 9, 2000
	A8	Arsenal 8 ounces per acre	May 9, 2000
[b]	A4O2	Arsenal 4 ounces per acre and Oust 2 ounces per acre	May 9, 2000
[b]	A4OS6.5	Arsenal 4 ounces per acre and Oustar 6.5 ounces per acre	May 9, 2000
	A4P1.2	Arsenal 4 ounces per acre and Pendulum 1.2 quarts per acre	May 9, 2000
	A6P1.2	Arsenal 6 ounces per acre and Pendulum 1.2 quarts per acre	May 9, 2000
	A4V24	Arsenal 4 ounces per acre and Velpar L 24 ounces per acre	May 9, 2000
[b]	OS13	Oustar 13 ounces per acre	May 9, 2000
[b]	02V24	Oust 2 ounces per acre and Velpar L 24 ounces per acre	April 7, 2000

[a]Treatments were applied over the top of the longleaf seedlings in a five feet band with a tractor/sprayer system at 15 gallons per acre.
[b]treatments that were followed for six growing seasons in replications 2, 3 ,and 4.

differences between the May treatments at the end of the first growing season (table 2). Survival at the end of the second growing season (all May treated plots and control plots were replanted in December 2000) ranged from 58 percent for the May Arsenal+Pendulum treatment to 91 percent for the Arsenal+Oustar for the May treatments and 90 percent for the April Oust+Velpar L treatment and 64 percent for the control. Second year survival for the Arsenal+Oustar treatment was significantly greater than the control, Arsenal at 6 ounces per acre, and the Arsenal+Pendulum treatments (table 2). Percent trees out of the grass stage ranged from 30 percent for the Arsenal at 8 ounces per acre and Arsenal+Pendulum treatment to 54 percent for the Arsenal+Oustar for the May treatments. There were no significant differences in percent seedlings out of the grass stage among the May treatments (table 2). The April Oust+Velpar L treatment had 81 percent of seedlings out of the grass stage at the end of the second growing season (table 2). Mean longleaf seedling height at the end of the second growing season ranged from 0.7 feet for the control and Arsenal+Pendulum treatment to 1.3 feet for the Arsenal+Velpar L treatment. There were no significant differences between the May treatments for year two height (table 2). The April Oust+Velpar L treatment longleaf seedlings were taller (1.6 feet) than all the May treatments by 0.3 to 0.9 feet at the end of the second growing season (table 2).

There were no significant differences for six year survival, d.b.h., height, or green weights per acre between the May treatments (table 3). May treatment six year survival ranged from 41 percent for the control treatment to 67 percent for the Arsenal+Oustar treatment (table 3). The April Oust+Velpar L treatment six year survival was 79 percent (table 3). Six-year heights ranged from 12.7 feet (Arsenal at 4 ounces per acre) to 13.7 feet (control) for the May treatments and 16.5 feet for the April Oust+Velpar L treatment (table 3). Six-year d.b.h ranged from 2.7 inches (Oustar at 13 ounces and Arsenal at 4 ounces per acre treatments) to 3.1 inches (Arsenal at 6 ounces per acre) and 3.5 inches for the April Oust+Velpar L treatment. Six-year green weight per acre estimated ranged from 5 994 pounds (Arsenal at 4 ounces per acre) to 9 579 pounds (Arsenal at 6 ounces per acre) for the May treatments and 18089 pound for the April Oust+Velpar L treatment (table 3).

Table 2—Longleaf pine herbaceous weed control trial mean survival, percent trees out of the grass stage, and height by treatment and measurement period on a former cotton field in Emanuel County, GA (fine-loamy well drained Tifton soil)

Application date	Treatment code[a]	Initial survival	Year one survival	Year two Survival[c]	Year two Trees out of grass stage	Year two Height
		---percent---				feet
May 2000	[b]C	62	51	64cd	32	0.7b
May 2000	[b]A4	64	54	76abcd	43	0.8b
May 2000	[b]A6	74	63	74abcd	47	0.9b
May 2000	A8	48	40	64cd	30	0.8b
May 2000	A4O2	61	56	81abc	52	1.2a
May 2000	[b]A4OS6.5	65	58	91a	54	1.2a
May 2000	A4P1.2	49	44	58d	35	0.8b
May 2000	A6P1.2	66	56	69bcd	30	0.7b
May 2000	A4V24	54	48	84ab	41	1.3a
May 2000	[b]OS13	52	44	84ab	42	1.2a
April 2000	02V24	91	90	90	81	1.6

[a]Refer to Table 1 for full treatment descriptions.
[b]Treatments that were followed for six growing seasons.
[c]Means followed by a different letter within a measurement period are significantly different using Duncan's Multiple Range Test at the 5 percent alpha level for the May treatments.

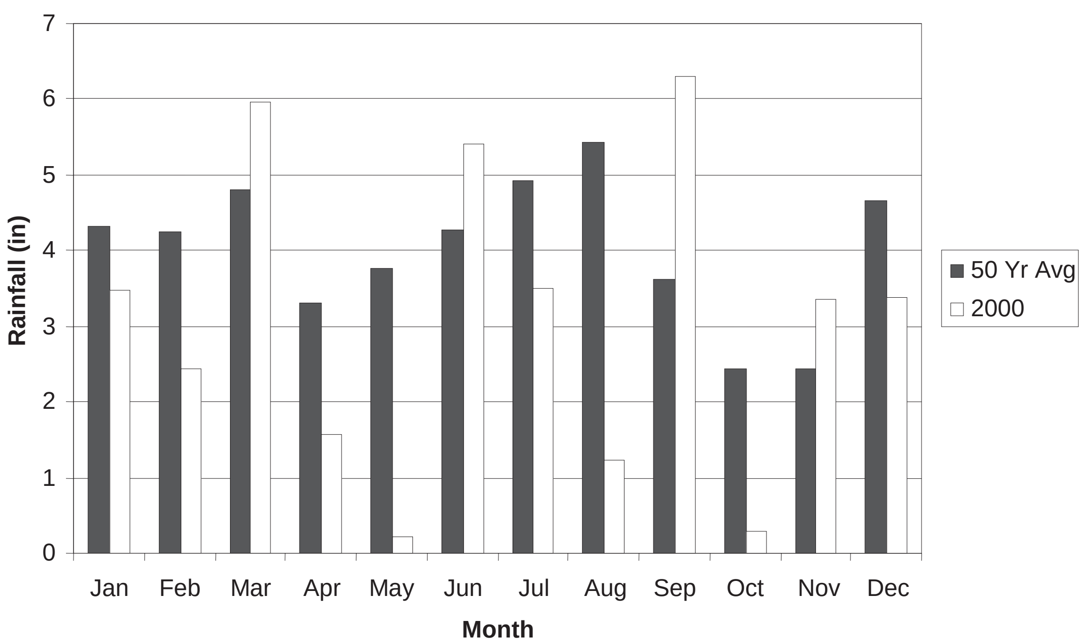

Figure 1—Vidalia, GA weather station rainfall patterns for the year 2000 and the 50 year average.

Table 3—Longleaf pine herbaceous weed control trial mean survival, height, d.b.h., and green weight per acre by treatment through March 2006 on a former cotton field in Emanuel County, GA (fine-loamy well drained Tifton soil)

Treatment date	Treatment code[a]	Year six			
		Survival	Height	D.b.h.	Green weight
		percent	*feet*	*inches*	*pounds per acre*
May 2000	C	41	13.7	3.0	6003
May 2000	A4	53	12.7	2.7	5994
May 2000	A6	59	14.4	3.1	9579
May 2000	A4O2	60	13.6	2.9	8482
May 2000	A4OS6.5	67	13.4	2.9	8026
May 2000	OS13	66	12.9	2.7	9270
April 2000	02V24	79	16.5	3.5	18089

[a]Refer to Table 1 for complete treatment description.
There were no significant differences between the May treatments six growing seasons after application.

SUMMARY AND DISCUSSION

Although the April 7, 2000 Oust+Velpar L banded herbicide treatment could not be statistically compared to the May treatments, it outperformed all the May 9, 2000 treatments and the control treatment for initial survival, first year survival, second year survival, percentage of trees out of the grass stage, second-year height, and six-year survival, d.b.h., height, and green weight per acre. The April Oust+Velpar L treatment area did not need a re-plant with 90 percent survival whereas the May treatments and the control plots were re-planted at the landowner's request. Second-year planted (December 2000) longleaf pines were compared to first-year (December 1999) planted longleaf in the May herbicide treated plots for d.b.h. and total height. The mean d.b.h. (3.4 inches) and total height (16.0 feet) from the first-year planted longleaf were significantly greater than the second-year planted longleaf (1.9 inches and 9.0 feet, respectively). There was not a second year (spring of 2001) banded herbicide application over any of the plot longleaf seedlings.

South Georgia experienced an excessive drought during 2000. The Vidalia weather station rainfall during 2000 was 11.4 inches below the fifty year average of 48.2 inches (fig. 1). Historically, April and May have been the two months with the lowest rainfall during the first half of the year for all interior Georgia Coastal Plain weather stations. April and May rainfall in 2000 totaled 1.8 inches, whereas the historic average is 7.1 inches for the Vidalia weather station. The April and May 2000 rainfall deficit accounted for 46.5 percent of the entire year's rainfall deficit. Note that the majority (81 percent on average) of first year mortality occurred between 8 May and 21 June for all treatments and the control during this very droughty period. For example, as of June 21, 2000 (six weeks after the May treatments and ten weeks after the April treatment) mortality ranged from 26 to 52 percent in the May herbicide treated plots and 9 percent in the April Oust+Velpar L plots (table 2). The end of the first growing season mortality ranged from 37 to 60 percent for the May treatments and 10 percent for the April treatment (table 2). This study illustrates that an early herbicide application on well drained upland soils during droughty spring conditions can be crucial for early survival, growth, stand uniformity, and reduce the need for replanting.

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EFFECT OF LIME STABILIZED BIOSOLIDS AND INORGANIC FERTILIZER APPLICATIONS ON A THINNED LONGLEAF STAND – TEN YEAR RESULTS

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Abstract—This project was initiated on the Sand Hills State Forest in Chesterfield County, SC in May 1995 to determine the benefits of inorganic fertilizer (NPK) and lime stabilized biosolids applications in a twice-thinned longleaf pine (*Pinus palustris* Mill.) stand planted in 1963 on an excessively well drained deep sand (Alpin soil series). Major objectives included quantifying the magnitude and duration of pine straw response, stand growth, and economics of each treatment over a ten-year period. The experimental design was randomized complete block design with three replications with treatments applied in the spring of 1995 and reapplied in the spring of 1999. Treatments were: control (no fertilizer), NPK, and lime stabilized biosolids. All living tagged trees in treatment plots were measured (d.b.h, total height) prior to the first application in March 1995 and re-measured in February-March 1997, 1999, June 2001, February 2003, and August 2005. Results indicate a significant near-term pine straw production benefit to NPK and the biosolids treatments in years 2 and 3 after the first application. Mean NPK and biosolids treatment plot basal area per acre and volume per tree increments during the periods 1999-2005 and 1995-2005 were significantly greater than the control. Mean NPK plot volume per acre increment was significantly greater than the control and biosolids plots during the period of 1995-1999. The NPK and biosolids plot volume per acre increments during 1999-2005 were significantly greater than the control. Ten year total volume per acre increment was significantly greater in NPK plots than in biosolids plots and biosolids plots were significantly greater than the control.

INTRODUCTION

The South Carolina Forestry Commission was interested in determining the benefits of two applications of inorganic fertilizer and the town of Cheraw lime stabilized biosolids in a mid-rotation thinned longleaf pine stand on the Sand Hills State Forest in Chesterfield County, SC in the spring of 1995. Major objectives included quantifying the magnitude and duration of (1) pine straw (litter layer dry weight) response, (2) soil available P and foliar N, P, and K trends over time by treatment, and (3) tree/stand growth (d.b.h., basal area (BA) per acre, height, volume per tree, volume per acre, and product class distributions; pulpwood (PW), superpulp (SP), and chip-n-saw (CNS)) response.

METHODS

The land use history of the study area was as follows. Prior to the longleaf planting, the site was a natural pine stand with a heavy turkey oak (*Quercus laevis* Walt.) understory that was clearcut in 1961. The site was mechanically cleared and planted to watermelons in 1962. The site was then planted to longleaf pine using bareroot seedlings at a 6 by 6 feet spacing in 1963. The longleaf stand was thinned twice: in 1984 from 90 square feet basal area per acre to 64 square feet BA per acre removing 3 cords per acre leaving 7.5 cords per acre, and in 1994 from 100 to 60 square feet BA per acre removing 7.6 cords per acre leaving 16 cords per acre. Stand management during the ten year study period included pine straw raking every other year from 1995 through 1999 with no understory hardwood control, then raking annually with controlling understory woody vegetation, primarily turkey oak, by stump cutting, piling, and herbicide treating the stumps from 2000 to 2005. The soil series was verified by a NRCS soil mapper as excessively well- drained deep sand (Alpin soil series; Lamellic Quartzipsamments).

The experimental design was randomized complete block design with three replications. Gross treatment plots (145 by 145 feet) were installed within the soil delineated stand. Permanent measurement plots (104.5 by 104.5 feet) were installed within each gross treated plot. Forty feet of untreated buffer separated each plot. Forest floor and surface soil samples were collected prior to fertilizer and biosolids treatments. Since spring growth had already initiated, foliage samples were not taken prior to plot treatment. All living longleaf trees in each permanent measurement plot were aluminum tagged (at 4.5 feet above groundline), numbered, and measured for d.b.h. and total height prior to plot treatment. Longleaf total and merchantable stem volume (wood+bark) was estimated using equations developed by Baldwin and Saucier (1983):

$$\text{Total Volume} = \log TV = -2.77009 + 1.04013 \log (D^2H)) \text{ and}$$

$$\text{Merchantable Volume} = MV = TV{*}R \quad (1)$$

$$\text{where } R = 1- 7.1949(Dm^{2.89957})/((D^2H)^{1.04094}), \quad (2)$$

Total Volume and Merchantable Volume in cubic feet, D=d.b.h. (inches), H=total height (feet), and Dm=top diameter (inches; 3 for PW, SP, and 6 inches for CNS)

Plots were randomly assigned a treatment. Treatments were as follows: control (no fertilizer), 10-10-10 at 1500 pounds per acre, lime stabilized biosolids (8 wet tons per acre; 40 percent solids, 4.5 wet tons = 1 ton agricultural lime, 210 pounds total-N, 80 pounds plant available-N, 110 pounds P_2O_5, 11 pounds K_2O, 1900 pounds Ca, and 6.4 pounds Mg per acre) first applied in May - June 1995. Plots were treated a second time in May - June 1999. The treatments were: control=no treatment, 10-10-10 at 1500 pounds per acre, and lime stabilized biosolids at 12 wet tons per acre

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(310 pounds total-N, 367 pounds P_2O_5, and 72 pounds K_2O per acre). All living tagged trees were re-measured (d.b.h. and total height) in February-March 1997, 1999, June 2001, March 2003, and August 2005. Surface soil (0-6 inches) and foliage samples were taken each January-February starting in 1996 through 2003 and 2005. Surface soil was analyzed for available phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) using the Mehlich I extract procedure and soil pH (AS-3000 pH analyzer 1:1 ratio of soil to deionized water). Foliage was analyzed for N (Dumas procedure), P, K, Ca, Mg, B, and Cu (HNO_3 + 30 percent H_2O_2 wet ashing). Six 144-square inch grids of forest floor litter layer (fresh brown needles representing straw that would be harvested) samples were taken per plot prior to the lime stabilized biosolids and inorganic fertilizer application in May-June 1995 and then each January-February after fertilizer application through February 1999. The stand was raked twice during the first four years of the study period then annually starting in 2000 making litter layer collection and analysis impractical. All litter layer samples were oven dried at 70 °C for 48 hours and weighed to determine dry weights per acre by treatment. A bale of longleaf pine straw was assumed to be 19 pounds of litter layer by dry weight (Morris and others 1992). Pine straw, soil, foliage, and tree/stand parameter means were tested by year for significant differences using Duncan's Multiple Range Test at the 5 percent alpha level.

RESULTS

Pine Straw Estimates

There were no significant pine straw (litter layer) gains with NPK or biosolids fertilization 9 months after initial application (table 1). This is to be expected as pine needles tend to stay on the tree for an average of 18 months (range of 1 to 2 years) (Gholz and others 1985). The second year post-NPK and biosolids application there were significant pine straw gains over the control of 1 812 and 1 292 pounds per acre, respectively (table 1). The plots that were fertilized with NPK or lime stabilized biosolids had significantly greater pine straw values in the third and fourth year after initial application (table 1). The control plots produced 4.82 tons per acre, the NPK treated plot produced 7.09 tons per acre, and the biosolids treated plots produced 6.52 tons per acre from May 1995 through February 1999. The NPK treated plots produced 2.27 extra tons per acre and the biosolids treated plots produced an extra 1.70 tons per acre over the control during this period. This equates to and extra $89 to $120 per acre (at $0.50 per bale and 19 pounds per bale dry weight) (Morris and others 1992) in pine straw revenues for the biosolids and NPK treatment, respectively during this period.

Soil Available Phosphorus

Surface soil (0-6 inches) available P (SA-P) prior to the first treatments (May 1995) means ranged from 0.33 to 3.5 ppm (table 2), concentrations considered to be below sufficiency for longleaf pine (Blevins and others 1986). Soil available P concentrations from the NPK plots in July 1995, September 1996, and February 1996 were significantly greater than SA-P in the control and biosolids plots. There were no significant SA-P treatment differences in 1997 (control; 3.5, NPK; 7.5 and biosolids; 11 ppm), 1999 (control and biosolids; 0 ppm and NPK; 6 ppm), and 2001 (control; 0.5, NPK 25, and biosolids; 3.3 ppm). SA-P was significantly greater in the NPK plots (8 ppm) than the biosolids (1.8 ppm) and control plots (0.5 ppm) in 1998, 2000 (control; 0.33, NPK; 21, and biosolids; 1.5 ppm), 2002 (control; 3.0, NPK; 21, and biosolids; 7.7 ppm), 2003 (control; 2.5, NPK; 32, and biosolids; 11 ppm), and 2005 (control; 3.5, NPK; 18, and biosolids; 7.0 ppm, table 2).

Foliar N, P, and K

Longleaf pine foliar N, P, and K concentrations were not significantly different by treatment in February 1996, but foliar N was below sufficiency (Blevins and others 1986) from the control plot trees (0.85 percent) and above sufficiency from the biosolids (1.1 percent) and the NPK plot trees (1.3 percent) nine months after the first treatment (table 2). Mean foliar N from the NPK plot trees (0.97 percent) was significantly greater than the biosolids (0.82 percent) and control plot trees (0.70 percent) in February 1997. Foliar P and K were not significantly different between treatments in 1997. Foliar N and P were not significantly different between treatments in February 1998 and 1999. Foliar K was significantly greater from the NPK plot trees (0.46 percent) than the biosolids (0.32 percent) and control (0.26 percent) in 1998. There were no significant treatment differences in February 1999 (table 2). Longleaf pine foliar N, P, and K

Table 1—Pine straw production estimates by treatment and measurement year from a 1963 planted longleaf stand (Alpin soil series) on the Sand Hill State Forest in Chesterfield County, SC

Treatment	Pinestraw production by year				
	1995	1996	1997	1998	1999
	---------------- *pounds per acre* ----------------				
Control	2390	1647	2000b	2191b	1417b
NPK	2123	1468	3812a	4035a	2745a
Biosolids	2123	1751	3202a	3555a	2400a

Table 2—Foliar nitrogen (N), phosphorus (P), potassium (K), and surface (0-6 inches) soil available P by treatment and measurement year from a 1963 planted longleaf stand (Alpin soil series) on the Sand Hill State Forest in Chesterfield County, SC

	Year									
Treatment	1995	1996	1997	1998	1999	2000	2001	2002	2003	2005
	---------- Foliar N (%) ----------									
Control		0.85	0.70c	0.82	0.88	0.88b	0.88	0.86	0.98b	
NPK		1.10	0.97a	0.96	0.87	1.58a	0.92	0.89	1.18a	
Biosolids		1.30	0.82b	0.88	0.82	0.89b	0.96	0.83	0.88b	
	---------- Foliar P (%) ----------									
Control		0.08	0.05	0.07	0.07	0.07b	0.07	0.08	0.09b	
NPK		0.08	0.08	0.09	0.07	0.11a	0.07	0.08	0.10a	
Biosolids		0.08	0.07	0.09	0.08	0.08b	0.08	0.14	0.09b	
	---------- Foliar K (%) ----------									
Control		0.32	0.20	0.26b	0.26	0.25b	0.28b	0.29	0.32b	
NPK		0.36	0.42	0.46a	0.43	0.54a	0.46a	0.40	0.47a	
Biosolids		0.58	0.28	0.32b	0.28	0.29b	0.32b	0.27	0.27b	
	---------- Soil P (ppm) ----------									
Control	0.3	0.0b	3.5	0.5b	0.0	0.3b	0.5	3.0b	2.5b	3.5b
NPK	3.6	16.0a	7.5	8.0a	6.0	21.0a	25.0	21.0a	32.0a	18.0a
Biosolids	1.8	0.0b	11.0	1.8b	0.0	1.5b	3.3	7.7b	11.5b	7.0b

Minimum sufficiency longleaf pine guidelines; foliage N=0.95 percent, P=0.08 percent, K=0.30 percent and soil available P=5 ppm (Blevins and others 1986).

Treatment means within a measurement year followed by a different letter are significantly different using Duncan's Multiple Range Test at the 5 percent alpha level.

concentrations from the NPK treatment (1.6 percent N, 0.11 percent P, and 0.54 percent K) were significantly greater than the biosolids (0.89 percent N, 0.08 percent P, and 0.29 percent K) and control (0.88 percent N, 0.07 percent P, and 0.25 percent K) in February 2000, nine months after the second biosolids and NPK treatment (table 2). Foliar N and P were not significantly different between treatments in 2001, but mean foliar K concentration from the NPK treatment (0.46 percent) was significantly greater than the biosolids (0.32 percent) and control (0.28 percent). Foliar N, P, and K were not significantly different between treatments in 2002. Foliar N, P, and K concentrations from the NPK treatment trees were significantly greater than the biosolids and control trees from the last year of foliage collection in February 2003 (table 2).

Tree and Stand Growth

Treatment means by year—There were not significant treatment mean differences for trees per acre, d.b.h., total height, total volume per acre, pulpwood (PW; 4.5 inches < d.b.h. <6.6 inches) volume per acre, and superpulp (SP; 6.6 inches ≤ d.b.h. < 8.6 inches) volume per acre during the ten year study period (tables 3 and 4). There was a significant chip and saw (CNS; d.b.h. ≥ 8.6 inches) volume per acre difference in 2005 with the NPK treatment producing more CNS volume (1,560 cubic feet per acre) than the control (1,199 cubic feet per acre) and the biosolids treatment (1,437 cubic feet per acre) not being significantly different than the NPK or control treatment (table 4).

Incremental means between measurement years—The NPK treatment basal area per acre increment (13.4 square feet per acre) during the first four years (March 1995 to March 1999) was significantly greater than the control (8.1 square feet per acre, table 5). The NPK total volume per acre increment (399 cubic feet per acre) was significantly greater than the biosolids (285 cubic feet per acre) and control (245 cubic feet per acre) between 1995 and 1999 (table 6). The NPK and biosolids d.b.h., basal area, volume per tree, and total volume per acre increment means during the second six year period were significantly greater than the control. Ten year (1995-2005) d.b.h, basal area, and CNS volume increment means from the NPK and biosolids treatments were significantly greater than the control (table 6). The NPK volume per tree increment (6.22 cubic feet) during the ten year period was significantly greater than the control (3.63 cubic feet) but not significantly greater than the biosolids (5.21 cubic feet). The NPK treatment produced significantly greater total volume per acre (1,059 cubic feet per acre)

Table 3—Trees per acre, d.b.h., total height, and volume per tree by treatment and measurement year from a 1963 planted longleaf stand (Alpin soil series) on the Sand Hill State Forest in Chesterfield County, SC

Year	Treatment	Trees per acre	d.b.h.	Total height	Tree volume
			in	*ft*	*ft³*
1995	Control	196	7.5	50.1	6.85
	NPK	177	7.3	49.7	6.52
	Biosolids	192	7.3	50.5	6.70
1997	Control	195	7.7	51.6	7.61
	NPK	175	7.8	51.5	7.75
	Biosolids	188	7.7	50.3	7.49
1999	Control	195	8.0	51.6	8.14
	NPK	175	8.2	52.7	8.50
	Biosolids	187	8.1	52.0	8.91
2001	Control	195	8.4	52.8	9.29
	NPK	175	8.9	53.6	10.50
	Biosolids	185	8.7	53.4	9.99
2003	Control	195	8.5	54.0	9.77
	NPK	175	9.1	56.0	11.60
	Biosolids	185	8.9	54.9	10.70
2005	Control	195	8.7	55.2	10.50
	NPK	175	9.4	57.6	12.70
	Biosolids	185	9.2	56.5	11.90

There were no significant treatment differences within each measurement year using Duncan's Multiple Range Test at the 5 percent alpha level.

than the biosolids (903 cubic feet per acre) and the biosolids produced significantly greater total volume than the control (699 cubic feet per acre) during the ten-year study period (table 6). There were no significant treatment differences for total height, PW, or SP volume increment during the study period (tables 5 and 6).

DISCUSSION

Prior to the first treatments, soil available P in the surface 6 inches (0 to 3.6 ppm, table 2) was below sufficiency for longleaf pine (Blevins and others 1986), making this site a good candidate for fertilization. Longleaf pine foliar N (0.85 percent) was below sufficiency, foliar P (0.08 percent) was at sufficiency, and foliar K (0.32 percent) was slightly above sufficiency from the control plot trees in the first sampling year (1996, table 2). Foliar N, P, and K concentrations from the control plot trees were at or below sufficiency from 1997 through 2002, indicating that this stand would respond to an NPK fertilizer treatment. The near-term (1995 through 1999) straw production rate was increased by an average 52 bales per acre per year with the first NPK application and 37 bales per acre per year with the first biosolids application. Ten year diameter increment for the NPK and biosolids plot trees were 0.9 (75 percent gain) and 0.7 inches (58 percent gain) greater than the control (1.2 inches, table 5). Basal area ten year increment for the NPK (32.5 square feet per acre) and the biosolids (28.9 square feet per acre) were 52 and 35 percent greater than the control (21.4 square feet per acre). The NPK and biosolids volume per tree increments (6.22 and 5.21 cubic feet) were 71 and 44 percent greater than the control (3.63 cubic feet) during the ten year study period (table 5). Total volume per acre was improved over the control by 84 and 29 percent or 0.42 cords per acre per year (1.1 tons per acre per year) and 0.24 cords per acre per year (0.64 tons per acre per year) with the two NPK and biosolids treatments, respectively (table 6). Chip and saw volume per acre production was improved by 47 and 33 percent with the two NPK and biosolids treatments, respectively compared to the control (table 6). Using Timber Mart-South (1995, 2005), SC pine stumpage prices, the NPK treatments improved wood value over the control by $342 per acre and the biosolids improved wood value by $209 per acre over the control. Adding in the increased pine straw revenues during 1997, 1998, and 1999 (at $0.50 per bale), the NPK wood plus pine straw revenues were $473 per acre greater than the control and the biosolids wood plus pine straw revenues were $303 per acre greater than the control.

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Table 4—Total volume, pulpwood, superpulp, and chip-n-saw volume per acre means by treatment and measurement year from a 1963 planted longleaf stand (Alpin soil series) on the Sand Hill State Forest in Chesterfield County, SC

Year	Treatment	Total volume	Pulpwood[1] volume	Superpulp[2] volume	Chip-n-saw[3] volume
		ft^3 $acre^{-1}$			
1995	Control	1338	146	761	308
	NPK	1144	149	638	251
	Biosolids	1303	145	784	256
1997	Control	1485	105	782	449
	NPK	1345	114	609	477
	Biosolids	1412	66	785	416
1999	Control	1583	74	759	579
	NPK	1543	93	592	683
	Biosolids	1588	63	650	679
2001	Control	1800	69	576	924
	NPK	1823	58	394	1122
	Biosolids	1837	47	568	991
2003	Control	1883	69	554	1020
	NPK	2003	38	381	1320
	Biosolids	1976	30	503	1181
2005	Control	2037	68	506	1199b
	NPK	2203	30	330	1560a
	Biosolids	2205	26	455	1437ab

[1]Pulpwood volume = 4.6 ≤ d.b.h. ≤ 6.5 inches to a 3 inch top.
[2]Superpulp volume = 6.6 ≤ d.b.h. ≤ 8.5 inches to a 3 inch top.
[3]Chip-n-saw volume = d.b.h. > 8.5 inches to a 6 inch top.
Treatment means within a measurement year followed by a different letter are significantly different using Duncan's Multiple Range Test at the 5 percent alpha level.

Table 5—D.b.h., basal area, total height, and volume per tree growth increments by treatment and measurement period from a 1963 planted longleaf stand (Alpin soil series) on the Sand Hill State Forest in Chesterfield County, SC

Year	Treatment	d.b.h.	Basal area	Total height	Tree volume
		in	ft^2 $acre^{-1}$	*ft*	ft^3
1995-1999	Control	0.5	8.1b	1.6	1.29
	NPK	0.9	13.4a	3.0	2.39
	Biosolids	0.8	10.6ab	1.5	1.80
1999-2005	Control	0.7b	13.3b	3.6	2.34b
	NPK	1.1a	19.1a	4.9	3.84a
	Biosolids	1.1a	18.1a	4.5	3.41a
1995-2005	Control	1.2b	21.4b	5.2	3.63b
	NPK	2.1a	32.5a	7.9	6.22a
	Biosolids	1.9a	28.9a	6.0	5.21ab

Treatment means within a measurement period followed by a different letter are significantly different using Duncan's Multiple Range Test at the 5 percent alpha level.

Table 6—Total volume, pulpwood, superpulp, and chip-n-saw volume per acre growth increments by treatment and measurement year from a 1963 planted longleaf stand (Alpin soil series) on the Sand Hill State Forest in Chesterfield County, SC

Period	Treatment	Total volume	Pulpwood[1] volume	Superpulp[2] volume	Chip-n-saw[3] volume
		------------------------------*ft^3 acre^{-1}*--------------------------			
1995-1999	Control	245b	-72	-2	271
	NPK	399a	-58	-45	432
	Biosolids	285b	-81	-134	424
1999-2005	Control	454b	-6	-253	620
	NPK	660a	-63	-262	877
	Biosolids	618a	-38	-195	758
1995-2005	Control	699c	-78	-255	891b
	NPK	1059a	-120	-308	1309a
	Biosolids	903b	-119	-329	1182a

[1]Pulpwood volume = 4.6 ≤ d.b.h. ≤ 6.5 inches to a 3 inch top.
[2]Superpulp volume = 6.6 ≤ d.b.h. ≤ 8.5 inches to a 3 inch top.
[3]Chip-n-saw volume = d.b.h. > 8.5 inches to a 6 inch top.
Treatment means within a measurement period followed by a different letter are significantly different using Duncan's Multiple Range Test at the 5 percent alpha level.

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EFFECTS OF LIQUID FERTILIZER APPLICATION ON THE MORPHOLOGY AND OUTPLANTING SUCCESS OF CONTAINER LONGLEAF PINE SEEDLINGS

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Abstract—Of a range of fertilization rates (0.5, 1.0, 2.0, 3.0, and 4.0 mg nitrogen (N) per seedling per week) applied for 20 weeks, the 2.0-N and 3.0-N seedlings produced good root collar diameter (RCD) growth (6.9 and 7.1 mm, respectively) and needle length ≤ 30 cm. Root collar development did not differ significantly in seedlings receiving the 4.0-mg-N treatment from those receiving 2.0-mg or 3.0-mg, but needles grew to 35 cm in 4.0-N, surpassing the 30-cm limit to avoid clipping. Seedling survival (95 percent) was higher in 3.0-N seedlings one year after outplanting. RCD growth in 3.0-N was 14 percent greater than 2.0-N seedlings, but not different between the 3.0-N and 4.0-N seedlings. Height and RCD growth remained statistically similar between 3.0-N and 4.0-N seedlings after 2 years. Emergence from the grass stage increased as the amount of fertilizer increased, but given similarities in field performance between the two highest N rates, the extra 1.0-mg N per seedling per week was not economically justified.

INTRODUCTION

Longleaf pine (*Pinus palustris* P. Mill.) once dominated the landscape of the Southern Coastal Plain of the United States, from eastern TX to southeastern VA, covering nearly 36 million ha (90 million acres) (Noss and others 1995). Development of the railroad system in the late 1800s and early 1900s across the Southern United States allowed intense harvesting of longleaf pine, drastically reducing its presence in the landscape (Outcalt 2000, Barnett 2002). Current estimates are that longleaf pine forests now occupy about 2.2 percent of the species' original range (Shibu and others 2006). Longleaf pine trees yield high quality logs, straight boles, and a high resistance to fire, insects, and disease when compared to other southern pine species (Gjerstad and Johnson 2002); and longleaf pine forests are critical to the survival of many unique, threatened, and endangered species (Outcalt 2000). For these reasons, recent Federal incentive programs have encouraged longleaf pine reforestation (Hainds 2002).

For decades, bareroot longleaf pine seedlings were used for reforestation. In the last decade, however, container production of longleaf pine seedlings has become a popular method used in regeneration (Dumroese and others 2005). In 2005, the number of container longleaf pine seedlings produced exceeded that of bareroot production by a margin of more than four to one (52 million versus 12 million) (Personal communication. 2006. Mark Hainds, Research Coordinator, The Longleaf Alliance, 12130 Dixon Center Rd, Andalusia, AL 36420). With their intact roots systems, container longleaf pine survive and grow better than bareroot stock on ideal or adverse planting sites (Boyer 1989, Barnett and McGilvray 1997, South and others 2005), a characteristic also noted for container loblolly pine (*P. taeda*) (South and Barnett 1986, Barnett and McGilvray 1993). The presence of an intact root system also decreases moisture stress and reduces transplant shock, allowing an extension of the traditional planting season (Barnett and McGilvray 1997).

Due to the increasing demand for container longleaf pine seedlings and the lack of detailed research dealing with container longleaf pine seedling production, Barnett and others (2002) published interim guidelines for producing quality container-grown longleaf pine. The guidelines describe preferred and unacceptable seedling specifications for needles, root collar diameter (RCD), the root system and root plug, and also container cavity size. Of these seedling attributes, RCD is the most important because it is well correlated with seedling performance after outplanting (South and others 1993, South and others 2005). The guidelines recommend that RCD should be at least 4.8 mm (3/16 inch), but preferably 6.3 mm (1/4 in) or greater. Achieving larger RCDs, however, requires application of additional nutrients, which can cause needles to grow long and potentially lodge with nearby seedlings (Dumroese and others 2005). Lodging can prevent efficient application of irrigation and fertigation solutions of container seedlings grown at very high densities (for example, >400/m^2 [40 ft^2]) and can cause needle mortality and allow foliar disease to develop (Barnett and McGilvray 1997). In many container nurseries, growers clip needles to discourage lodging.

In bareroot nurseries, the timing, frequency, and severity of clipping and seedling phenology can affect survival after outplanting, but in most studies a modest clipping of needles prior to outplanting improved survival, apparently through reductions in transpiration (South 1998). It is unclear if the results found for bareroot production would be similar for container seedlings grown at much higher densities and where seedling root mass is not lost during lifting. Barnett (1984) found that repeated clipping of needles to a short length (5 cm [2 inches]) reduced root system size. This finding led to the interim guideline to refrain from clipping needles to a length less than 10 cm (4 inches) (Barnett and others 2002). Identification of a nitrogen fertilization rate that promoted RCD development without excessive needle growth could allow nursery managers to avoid this labor-intensive nursery practice, especially if optimum outplanting performance could be maintained. Therefore, our objectives were to: 1) compare morphological and physiological characteristics of container

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longleaf pine seedlings grown under five liquid fertilizer regimes; and 2) evaluate subsequent survival and growth after outplanting.

MATERIALS AND METHODS

Greenhouse Experiment

The experiment took place in a greenhouse at the U.S. Forest Service, Southern Research Station in Pineville, LA (Lat 31.359 N, Long 92.436 W). Longleaf pine seed were obtained from Louisiana Forest Seed Company (Woodworth, LA) and sown on April 24, 2004, into Ropak® Multipot #3-96™ containers. Each container consisted of 96 cavities (441 seedlings/m^2 [41/ft^2]) with a volume of 98 cm^3 (6 cubic inches) and depth of 12 cm (4.8 inches). Cavities were filled with a 1:1 (v:v) peat moss to vermiculite medium.

Five weeks after sowing, five fertilizer treatments: 0.5, 1.0, 2.0, 3.0, and 4.0 mg nitrogen (N) per seedling per week for 20 weeks (weeks 6 through 25) were applied using Peter's Professional Brand™ 20-19-18 (20N:8P:15K) liquid soluble fertilizer. Two additional applications of fertilizer occurred, using the same N levels, during week 28 and week 32 (first and last week of November, respectively). For each treatment we used 12 containers (60 containers total).

Seedlings were irrigated whenever the container weight dropped to 75 percent of the field capacity weight (see Landis and others 1989). Once a week, the amount of fertilizer to add to a sufficient amount of irrigation water was calculated in order to apply the appropriate mg-N/seedling and return the containers to field capacity. Fertilizer solutions were carefully applied by hand using a watering bucket to ensure even distribution of the fertilizer.

Beginning nine weeks after sowing (June 21) and continuing at 5 week intervals, 30 seedlings were randomly sampled 6 times from each treatment. This resulted in 4 samples during the 20 week fertilizer application period, whereas the fifth and sixth samples were collected outside the application period, in November and December, respectively. Seedling RCD (mm) and length of the longest needle (cm) were measured. After carefully washing the roots, shoots and roots were separated and dried at 70 °C (160 °F) for 48 hours to determine dry root and shoot biomass (g). Once dried, samples were finely ground and analyzed for N concentration using a LECO-2000 CNS Elemental Analyzer (LECO Corp., St. Joseph, MI). For each dependant variable, data were analyzed using analysis of variance and when appropriate, means were compared using Duncan's multiple range test (SAS 2003).

Field Experiment

On November 17, 2004, 100 randomly selected seedlings from each treatment were outplanted on an open, mowed field site in the Palustris Experimental Forest near McNary, LA (Lat 31.017 N Long 92.617 W). The area is gently sloping (1 to 3 percent) with Beauregard silt-loam (fine-silty, thermic Plinthaquic Paleudults) soils that are moderately drained and slowly permeable (Kerr and others 1980). The site develops a perched water table during prolonged wet periods in winter and can be droughty in summer (Kerr and others 1980). The site was divided into four blocks, with 25 seedlings per treatment per block. Before outplanting, the RCD of each seedling was measured and labeled to facilitate re-measurement. In order to reduce competition and promote growth release, herbicide (Accord™) was applied around each planted seedling on May 10, 2005. One year after outplanting, we re-measured seedling RCD and calculated survival. On December 11, 2006, we re-measured RCD and measured the height (cm) of each seedling. We considered seedlings out of the grass stage when they reached ≥ 10 cm in height and ≥ 25 mm RCD (Wahlenberg 1946). We analyzed all dependent variables using logistic regression (SAS 2003).

RESULTS

Greenhouse Experiment

After 20 weeks of fertigation—The day prior to the initial fertilizer application (during week 5), seedlings were randomly selected and analyzed for N concentration, averaging 5.2 percent N. From that point, root and shoot N concentrations decreased in every rate but total N content increased, more so as N application rate increased (fig. 1). Increasing the N fertilization rate increased seedling size (table 1). All rates ≥ 1.0-mg-N/seedling/week resulted in seedlings having RCDs > 4.6 mm; these rates were not different. The 0.5-N rate, however, yielded seedlings with smaller RCD (3.7 mm) than the other N rates. For needle length, 3.0-N and 4.0-N produced the longest needles (28 and 30 cm, respectively), which were longer than 1.0-N and 2.0-N needles (24 and 22 cm, respectively). The 0.5-N rate had the shortest needles (20 cm), not significantly different than the 1.0-N seedlings. Every increased rate of N application resulted in increasing amounts of shoot biomass, ranging from 0.6 g at 0.5-N to 1.7 g at 4.0-N. Root biomass was an exception, the highest rates of N (3.0 and 4.0) had 0.6 g biomass, significantly less than 1.0-N and 2.0-N which averaged 0.7 g. Like the other variables, 0.5-N was significantly different and lowest at 0.5 g.

After 30 weeks of fertigation—The two additional applications of fertilizer made during weeks 28 and 32 caused total N content to increase, except at 4.0-N. For all rates, root N content continued to increase, but shoot N content either remained steady or declined (fig. 1). RCD was ≥ 6.9 mm for rates ≥ 2.0-N; these were statistically different than the 6.2 mm for 1.0-N which was statistically different than the 4.6 mm yielded by 0.5-N (table 2). Needle length decreased significantly from 35 cm in 4.0-N to 21 cm in 0.5-N. Shoot and root biomass followed the same general trend (table 2).

Field Experiment

First-year survival was high (80-95 percent) in all treatments and did not differ significantly among treatments (P = 0.6165). Interestingly, Block 1 had significantly lower survival (78 percent; P = 0.0073) compared to the other Blocks, which had survival rates of 90-92 percent. Similarly, Block 1 had significantly less (P = 0.0001) RCD growth (7.6 mm) when compared to the other Blocks (8.4 to 8.9 mm). The RCD increment was significantly different among treatments (P < 0.0001), ranging from 124 percent to 184 percent of original RCD, and increased with increasing rate of N applied in the greenhouse (fig. 2).

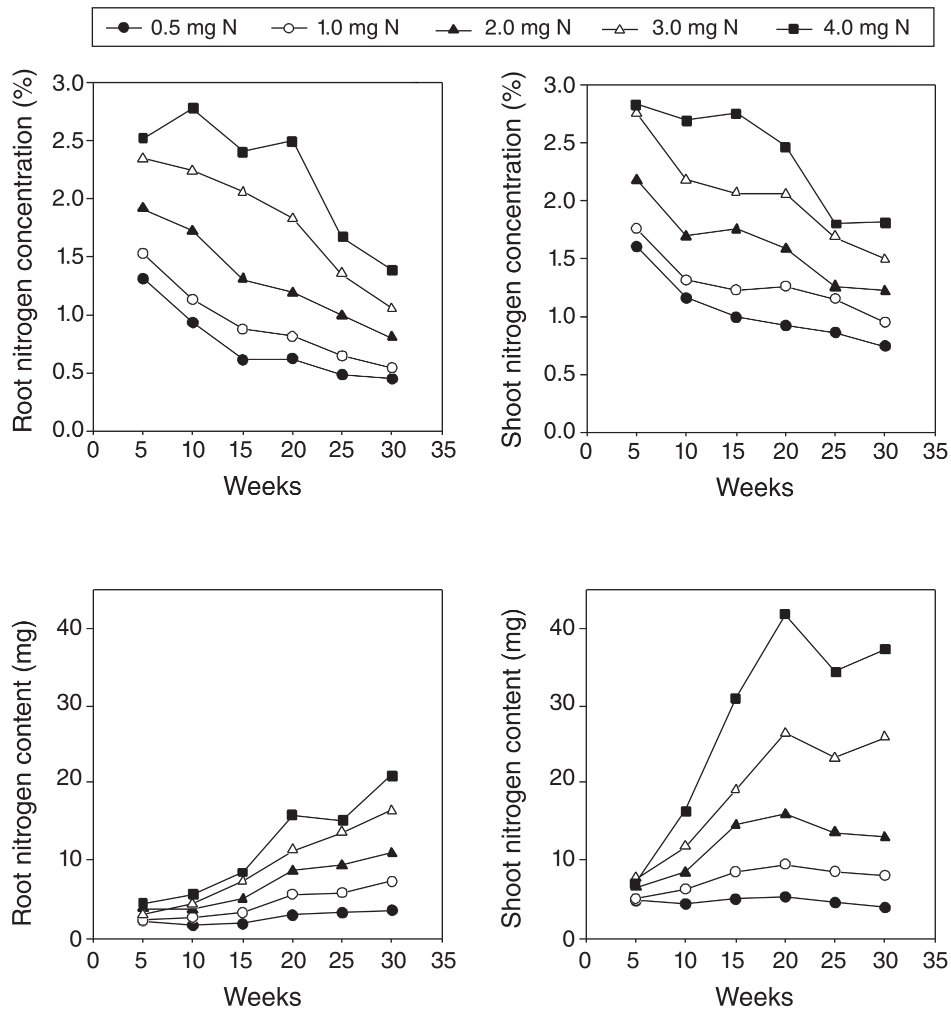

Figure 1—Root and shoot nitrogen concentrations (%) and contents (mg) of longleaf pine seedlings grown in containers in a greenhouse in Louisiana. Seedlings received five treatments: 0.5, 1.0, 2.0, 3.0, or 4.0-mg-N per seedling per week for 20 weeks, and then twice more during weeks 28 and 32.

Seedling survival after 2 years remained high (79-84 percent) and was significantly different among N treatments (P = 0.0248). Survival of the 0.5-N (81 percent) and the 4.0-N seedlings (79 percent) was significantly less than the 3.0-N seedlings (94 percent). No significant differences in survival occurred among the 1.0-N, 2.0-N, and 3.0-N treatments, which averaged 89 percent. The RCD increment increased with increasing N treatment after 2 years (P = 0.0001). The 3.0-N and 4.0-N treatments were not different, but their RCD increased significantly more than the lower N rates (table 3). The 0.5-N and 1.0-N seedlings did not differ in RCD growth after 2 years (table 3).

Grass stage emergence was different among treatments as N rates increased (P = 0.0001). The 0.5-N treatment had less RCD than 1.0-N, but both were similar in seedling height, while neither grew to the height (10 cm) or RCD (25 mm) necessary for seedlings to exit the grass stage (table 3). Treatments ≥ 2.0-N met the criteria for grass stage emergence with 2.0-N having less height and RCD than 3.0-N and 4.0-N, while the latter two rates did not differ in either growth category (table 3).

DISCUSSION

For container longleaf pine, reported rates of N application varied from 2 to 5 mg-N/week for 20 weeks (see Dumroese and others 2005). In this study, five rates were chosen in order to determine N application rates that yielded growth parameters deemed important from a seedling quality standpoint. RCD may be the single most important seedling quality parameter because increasing RCD is associated with enhanced outplanting performance (South and others 1993, South and others 2005). We found that increasing the rate of N from 0.5 to 3.0 mg per seedling per week increased RCD in the greenhouse, as well as in the first year after outplanting. Other researchers have also reported that increasing fertilizer rates to longleaf pine seedlings increases RCD during nursery production (Jose and others 2003, Dumroese and others 2005), a trait also reported in loblolly pine (Sung and others 1997), black spruce (*Picea mariana*)

Table 1—Mean (standard error) for seedling morphological characteristics after 20 weeks of fertilization

Nitrogen fertilizer rate (mg/seedling/week)	Root collar diameter (mm)	Longest needle length (cm)	Root biomass (g)	Shoot biomass (g)
0.5	3.7 (0.1) b	20.0 (0.9) c	0.48 (0.03) c	0.58 (0.02) e
1.0	4.6 (0.1) a	22.0 (0.9) cb	0.70 (0.03) a	0.76 (0.04) d
2.0	4.9 (0.2) a	24.2 (1.0) b	0.73 (0.03) a	1.01 (0.05) c
3.0	4.7 (0.2) a	27.6 (1.2) a	0.62 (0.03) b	1.29 (0.07) b
4.0	5.0 (0.2) a	30.4 (1.3) a	0.64 (0.02) b	1.70 (0.06) a
P value	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Different letters within columns indicate significantly different means using Duncan's multiple range test at alpha = 0.05.

(Quoreshi and Timmer 2000, Timmer and Teng 2004), and Norway spruce (*P. abies*) (Kaakinen and others 2004).

Shoot biomass also increased as N levels increased. Root biomass, however, reacted differently. The lower rates (1.0 and 2.0) produced more root biomass during the 20 week fertigation period than the higher rates (3.0 and 4.0). Similar findings have been reported for sugar pine *(P. lambertiana*), Jeffrey pine (*P. jeffreyi*) (Walker 2001), Douglas-fir (*Pseudotsuga menziesii*) (Jacobs and others 2003), Norway spruce (Kaakinen and others 2004), and longleaf pine (Prior and others 1997). This response to lower N levels—more root growth—may be the seedling's attempt to acquire additional nutrients. The 0.5-N rate, however, yielded the lowest root biomass, indicating insufficient N availability and probably a severe N deficiency.

Nitrogen concentrations in the shoots and roots decreased in each treatment over the course of the experiment, while total N content in seedlings increased. These trends are similar to previous study results with longleaf seedlings (Dumroese and others 2005). Seedlings given the highest N rate (4.0) had a foliar N concentration of 2.5 percent after the 20 week fertigation period. This is at the upper end of the optimum range for conifer seedlings (Landis and others 1989) and perhaps borderline for luxury consumption (Dumroese 2003). The next lower rate (3.0-N) yielded a foliar N concentration of 1.8 percent, a value still within the optimum range, but all rates ≤ 2.0-N yielded foliar N concentrations below that optimum range (Landis and others 1989). As the seedlings "coasted" from week 25 through week 35, the two additional applications of fertilizer were insufficient to maintain N concentrations; increased seedling biomass resulted in a dilution effect despite increases in seedling N content. Before outplanting, N concentration in the highest N application rate dropped from 2.5 to 1.4 percent, thereby moving below the optimum range for conifer seedlings (Landis and others 1989). Similar changes were seen in all other N application rates, but despite these drops, seedlings having received at least 1.0 mg-N/week continued to add RCD, needle length, and biomass.

At outplanting, all seedlings grown using rates ≥ 1.0-N exceeded many of the minimum guidelines described by Barnett and others (2002). Survival was not affected by the rate of N, but the rate of application did have an effect on RCD. The increment of new RCD increased as the rate of N applied in the greenhouse increased. This trend continued for 2 years with both RCD and height growth. Wahlenberg (1946) used a height of 10 cm and RCD of 25 mm as a guideline to determine when seedlings emerge from the grass stage.

Table 2—Mean (standard error) for seedling morphological characteristics after 30 weeks of fertilization

N fertilizer rate (mg/seedling/week for 20 weeks + 2 additional applications)	Root collar diameter (mm)	Longest needle length (cm)	Root biomass (g)	Shoot biomass (g)
0.5	4.6 (0.2) c	20.6 (0.7) d	0.81 (0.04) c	0.53 (0.03) e
1.0	6.2 (0.2) b	22.7 (1.1) cd	1.35 (0.05) b	0.86 (0.05) d
2.0	6.9 (0.2) a	24.9 (0.9) c	1.37 (0.04) b	1.07 (0.04) c
3.0	7.1 (0.2) a	29.6 (1.3) b	1.57 (0.08) a	1.74 (0.08) b
4.0	7.2 (0.2) a	35.0 (1.2) a	1.52 (0.09) a	2.06 (0.09) a
P value	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Different letters within columns indicate significantly different means using Duncan's multiple range test at alpha = 0.05.

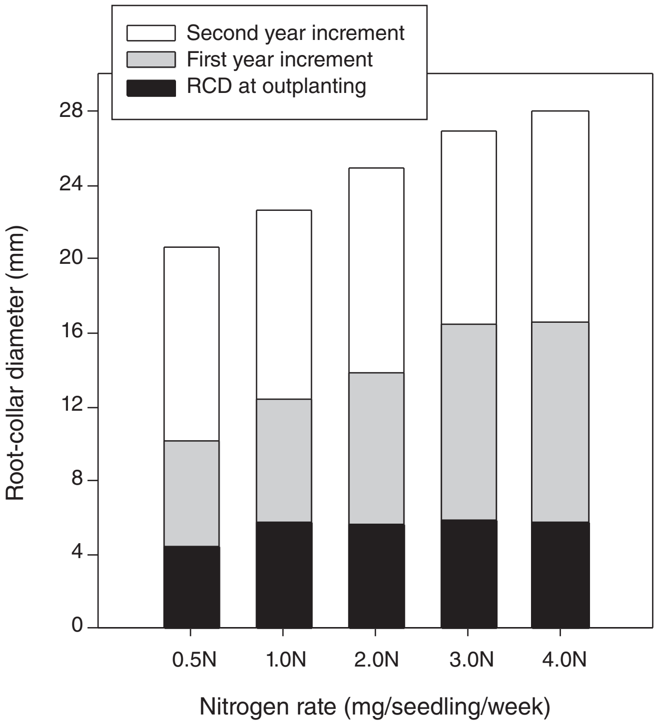

Figure 2—Root collar diameter growth of longleaf pine seedlings grown in containers in a greenhouse in Louisiana. Seedlings received five treatments: 0.5, 1.0, 2.0, 3.0, or 4.0 mg N per seedling per week for 20 weeks, and then twice more during weeks 28 and 32. The black portion of each bar represent RCD growth in the nursery; the gray portion is the RCD increment of growth added after one season in the field; the white portion is the RCD increment of growth added after two seasons in the field.

Based on these criteria, 62 percent of 3.0-N and 67 percent of 4.0-N seedlings had begun height growth 2 years after outplanting. The 2.0-N seedlings had 44 percent out of the grass stage, while height and RCD at this N level averaged 10 cm and 25 mm, respectively. Block 1 in the outplanting study had more grasses and woody stems, leading to significantly lower RCD and survival compared to the other three blocks. The percentage of seedlings exiting the grass stage would have been greater if Block 1 contained less competition. Deficiencies in nutrients, moisture, or sunlight can extend the time seedlings spend in the grass stage, which can differ from seedling to seedling. With a higher percent out of the grass stage, it appears 3.0-N and 4.0-N seedlings are able to more effectively compete for resources.

Because most longleaf pine seedlings emerge from the grass stage when RCD ≥ 25 mm (Wahlenberg 1946), producing seedlings with large RCDs in the nursery may shorten the time seedlings remain in the grass stage. Increased applications of N during hardening are known to foster RCD growth (Montville and others 1996) and recent work (South and others 2005, South and Mitchell 2006) indicate that RCDs in this container type (Ropak #3-96) could approach 11 mm before field performance might be compromised. For the containers used and the length of the growing season, however, it may be difficult to achieve much greater RCD growth. We grew longleaf seedlings with RCDs ≥ 6.9 mm using N rates ≥ 2.0-N. In particular, the 3.0-N or 4.0-N seedlings were similar in RCD and root biomass, but the 4.0-N seedlings were borderline for needing clipping to prevent lodging. Therefore, it appears that the benefit of adding an additional 1.0-mg N per week (3.0 to 4.0 mg) during the growing season was negligible in terms of seedling growth in the nursery, as well as survival and growth after outplanting. Seedlings at the 4.0 N-level were probably in or near to luxury consumption.

Finding an ideal N regime, however, will be difficult because of the enormous number of container types and N rates that could be used to grow longleaf seedling crops. Unfortunately, the optimum rate of N for any particular species in any particular nursery depends on many factors, including the idiosyncrasies and management philosophy of the nursery manager (Dumroese and Wenny 1997). From the studies we have considered, including our own, it appears that growers using Ropak Multipot #3-96 can produce seedlings with high survival and growth potential using a N application rate of

Table 3—The least squared means for initial (standard error) root collar diameter of seedlings outplanted in November 2004, diameter increment growth from 2004 until November 2006, final diameter measured in 2006, and final height measured in 2006

	Diameter			
Treatment	Initial (2004)	Increment (2004 to 2006)	Final (2006)	Height & (standard error))
0.5	4.53 (0.09) a	16.16 (0.62) a	20.64 (0.62) a	7.56 (0.73) a
1.0	5.72 (0.09) bc	17.00 (0.60) a	22.70 (0.60) b	8.45 (0.70) a
2.0	5.59 (0.09) bc	19.35 (0.60) b	24.90 (0.60) c	10.70 (0.71) b
3.0	5.95 (0.09) c	21.05 (0.58) c	26.93 (0.58) d	13.48 (0.68) c
4.0	5.74 (0.09) bc	22.40 (0.63) c	28.04 (0.63) d	14.46 (0.74) c
P value	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Different letters within columns indicate significantly different means using Duncan's multiple range test at alpha = 0.05.

3.0 mg N/seedling/week over a 20-week period, without the labor of clipping. This rate corresponds well with Dumroese and others (2005) and would be a good starting point for developing fertilization regimes specific to local nurseries.

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LONGLEAF PINE BUD DEVELOPMENT: INFLUENCE OF SEEDLING NUTRITION

J. P. Barnett, D. P. Jackson, and R. K. Dumroese[1]

Abstract—A subset of seedlings from a larger study (Jackson and others 2006, 2007) were selected and evaluated for two growing seasons to relate bud development, and root-collar diameter (RCD), and height growth with three nursery fertilization rates. We chose seedlings in the 0.5 (lowest), 2.0 (mid-range), and 4.0 (highest) mg of nitrogen per seedling treatments. Buds moved through three developmental phases and we confirmed that when RCD reached 25 mm (1 inch), seedlings were usually ≥ 10 cm (4 inches), had elongated buds, and were exiting the grass stage. After two growing seasons, heights greater than 10 cm (4 inches) were reached on 20, 60, and 65 percent of the 0.5, 2.0, and 4.0-N seedlings, respectively. On average, higher N rates yielded seedlings with larger RCDs, taller heights, and more seedlings exiting the grass stage. On an individual seedling basis, however, we detected a reduction in RCD increment growth with increasing RCD at outplanting across all fertilizer treatments. This phenomenon may be related to root binding, but we have insufficient data to confirm the nature of this response. Further studies are needed to resolve this issue.

INTRODUCTION

The longleaf pine (*Pinus palustris* P. Mill.) grassland forest of the southern Coastal Plain is among the most endangered ecosystems in North America (Noss and others 1995). Its native range once stretched from southern VA to east TX, covering almost 90 million acres. Now, the species occupies only about 2.2 million acres spread across the southern landscape in isolated patches (Shibu and others 2006). The thoroughness of the harvest and unique characteristics of the species have made regeneration difficult (Wahlenberg 1946).

The grass-stage nature of the species, a unique silvical characteristic, is poorly understood. Lack of seedling shoot elongation for a number of years after outplanting has contributed to longleaf pine's infrequent regeneration success. This, combined with application of management practices designed for loblolly (*Pinus taeda* L.) and slash (*Pinus elliottii* Engelm.) pines, resulted in frequent regeneration failures. As a result, attempts to regenerate longleaf pines have been largely avoided for many years in favor of other species.

In this paper, we will review the status of knowledge of bud development of longleaf pine, relate bud condition to initiation of seedling height growth, and report the response of seedling buds to application of varying nutrient regimes in the nursery.

BOTANICAL CHARACTERISTICS

Longleaf pine is a long-lived, native, evergreen conifer with scaly bark. Needles are in bundles of 3; they are slender, dark green, and 20 to 46 cm (8 to 18 inches) long. Cones are 15 to 25 cm (6 to 10 inches) long. Generally, seeds/kg (pound) equals 10,800 (4,900). The wintering buds are typically large with silvery-white scales. Compared to other southern pines, many of its characteristics are very distinctive (Boyer 1990). Survival and growth are closely related to longleaf pine's unique, silvical characteristics: its lack of seed dormancy that results in fall germination, its well-known grass stage and delayed height growth, and its high resistance to fire damage (Croker and Boyer 1975).

While in the grass stage, seedlings develop extensive root systems. Development can be followed by observing increases in RCD. When it approaches 2.5 cm (1 in), active height growth is imminent. Grass-stage seedlings, once they reach 0.8 cm (0.3 in) in root-collar diameter, are highly resistant to fire, even during the growing season. Seedlings in early height growth, up to a height of about 0.6 to 0.9 m (2 to 3 ft), become susceptible to damage by fire. Once beyond this stage, longleaf pines are again fire resistant depending on fire intensity (Bruce 1951, 1954).

Longleaf pine is intolerant of competition and considered a fire sub-climax species because fire is necessary to reduce hardwood overstories that readily overtop this species while in the grass stage (Croker and Boyer 1975, Wakeley and Muntz 1947, Wells and Shunk 1938). The species will grow best in the complete absence of competition, including that from other members of the species. Longleaf seedlings will usually survive for years under an overstory of parent pines. Growth, however, is very slow. Seedlings respond promptly with an increased rate of growth when released from overstory competition (Boyer 1990).

Brown-spot needle blight [*Mycosphaerella dearnessii* M.E. Barr; syn. *Scirrhia acicola* (Dearn.) Siggers 1932] can have great impact on the rate of seedling development and extend duration of the grass stage. During several decades following the massive harvest of longleaf pine, many seedlings remained in the forest floor infected with brown-spot needle blight. These provided a source of the fungus that infected newly planted seedlings and reduced seedling survival, vigor, and initiation of height growth. Prescribed fire was frequently used to destroy foliage infected by the disease (Grelen 1978, Pessin 1944, Siggers 1932). During more recent years, the source of inoculum has been greatly reduced and the disease is not a major problem if seedlings enter height growth within 2 or 3 years.

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While seedlings are in the grass stage, no distinct annual rings are evident in either the root or stem. Spring and summer wood are distinguished only after true terminal buds are formed (Pessin 1934). There is no way to determine how long seedlings may have remained in the grass stage.

BUD DEVELOPMENT AND INITIATION OF HEIGHT GROWTH

Development of buds during the grass stage is slow and can take several years. Pessin (1939) and Wahlenberg (1946) report that terminal buds go through several developmental stages. They classified the buds in three stages. The first stage is "*pincushion*"—a term suggested by Wakeley (1954). The fascicular meristem lies in a horizontal plane forming a flat surface or slightly convex masses of small, unopened needle sheaths or exposed, upward-pointing needle tips. Few or no discernable bud scales are present. Second, "*round*"—a slight convex curvature develops in this fascicle-bearing surface and a semblance of a bud appears. Few if any are longer than thick, covered with either hard and white or soft, felt-like brown scales. Third, "*elongated*"— buds cylindrical, longer than thick with pointed, conical tips, and covered with white scales. These buds develop into the main axis from which the fascicles arise laterally (Wakeley 1954). After the elongated bud develops, elongation of the main axis is rapid (Pessin 1939).

Wahlenberg (1946), based on many observations, defined that seedlings had exited the grass stage when they were ≥ 10 cm (4 inches) in height, and that this height growth was achieved when RCD reached 25 mm (1 inch). Pessin (1939), Wakeley (1954), and others who have done extensive research with longleaf pine seedling establishment have confirmed these relationships.

PHYSIOLOGICAL STUDIES OF GRASS-STAGE SEEDLINGS

Longleaf pine seedlings lack epicotyl elongation and do not exhibit shoot growth until two or more years after outplanting. Allen (1960, 1964) and Brown (1958, 1964) have conducted the most thorough evaluations of the physiology of bud development in grass-stage seedlings. Their research shows that growth promoting and inhibiting substances change as longleaf seedling buds enter their elongation phase. Their studies could not identify any biochemical or physiological rationale for seedlings remaining in the grass-stage condition, or of any product which, when applied, would effectively shorten the grass stage if applied to buds. Kossuth (1981) and Kraus and Johansen (1959) applied plant growth regulators to longleaf buds in the pincushion stage with no or limited growth response. Hare (1984) applied cytokinnin-like substances to grass-stage seedlings and obtained a stimulatory effect. After seven decades of research, however, the longleaf pine grass stage remains an enigma.

Because longleaf pine seedlings are adapted to fire regimes, they resprout needles quickly if defoliated by fire while in the grass stage. The terminal bud is protected by the surrounding dense needle cluster. In addition, underground root reserves enable longleaf seedlings to bolt from the grass stage when the carbohydrate-rich taproot becomes sufficiently large to propel the terminal bud above flame lengths (Platt and others 1988).

RESPONSE TO NUTRIENT APPLICATIONS

Early Observations

The relation between seedling RCD and emergence from the grass stage has been known for many years (Allen 1953, Hinesley and Maki 1983, Lauer 1987, White 1981). For bareroot seedlings, tree height after outplanting increases with increasing seedling RCD, however, best height performance occurs when seedlings are outplanted with RCDs greater than 10 mm (0.4 inch) (Lauer 1987, White 1981). Survival is not as consistently related to seedling RCD at planting; if RCD exceeds 10 mm, both the smallest and largest seedlings tend to have acceptable rates of mortality.

Although relationships between RCD and emergence from the grass stage are known, little emphasis has been given to nursery nutrient regimes needed to achieve consistent seedling sizes. It may be possible to shorten the grass stage by increasing seedling quality, which does not necessarily correspond to seedling size (Wakeley 1954). Hinesley and Maki (1983) reported that fall fertilization in the bareroot nursery resulted in substantial overwintering dry weight gains and increases in nutrient content and concentrations in one year old longleaf pine. In the field, the rate of emergence from the grass stage and subsequent height growth were improved by this fall fertilization treatment.

In recent years, nursery production of longleaf pine planting stock has shifted markedly from bareroot to container production. Although container technology has developed rapidly, little research has been done to evaluate container stock quality and field performance. South and others (2004) did find container seedling RCD was related to root growth potential and field survival, and they demonstrated a strong relationship between second year RCD (they call it ground-line diameter) and emergence from the grass stage. Results of this study, however, indicate that seedling quality can decline if seedling size becomes too large for the container.

Dumroese and others (2005) report a wide disparity of recommended fertilizer rates to use in container production of longleaf pine. Unfortunately, we lack good empirical data to suggest appropriate fertility guidelines for producing quality container longleaf seedlings.

Current Studies

Jackson and others (2006, 2007) conducted a study to relate morphology, nutrition, and bud development of longleaf pine seedlings to five different fertilizer application rates: 0.5, 1.0, 2.0, 3.0, and 4.0-mg N (nitrogen) per seedling. Each treatment consisted of 12 containers (each with 96 cavities)—3 replications of 4 containers each. One hundred seedlings randomly selected from each treatment were outplanted in four 25-seedling rows for field evaluations. Seedling RCDs were recorded at the time of outplanting.

Bud Development Study

To evaluate bud development from the Jackson and others (2006) study, a subset of seedlings were selected for additional RCD, height, and bud evaluations in year 2 after outplanting. Five seedlings from each replication were selected in March 2006 from the 0.5, 2.0, and 4.0-N treatments. To reduce variability, seedlings selected for the bud evaluations were within 1 mm of the average RCD for the selected treatments of the main study.

Our study objective was to evaluate bud development of longleaf pine seedlings throughout the second growing season after outplanting and relate performance data (RCD, height) to the three nursery fertilizer application rates.

Measurements—RCDs and heights were measured and photos of buds were taken on six dates during the second year after planting (table 1). These data were combined with measurements and photos taken at the time of outplanting and at the end of the first year in the field.

Results—On average, all seedlings increased RCD growth after outplanting, but the rate of increase was higher for the 2.0-N and 4.0-N fertilizer treatments than 0.5-N (fig. 1). These two treatments had similar slopes, indicating similar accrual of RCD. Moreover, we found that a RCD of 25 mm was the point where most seedlings emerged from the grass stage, that is, achieved heights ≥ 10 cm as established by Wahlenberg (1946) (fig. 2). This was confirmed with the larger Jackson and others (2007) dataset.

Seedlings of the 0.5-N treatments had the smallest RCDs when planted and throughout the study. Even after two full years, average RCD did not reach the point where they were initiating height growth (table 1). Both the 2.0- and 4.0-N treatments were superior to the 0.5-N treatments, but differences between these higher N rates were small (fig. 1, table 1). Both reached 25 mm in RCD during the summer months of the second year in the field, and only about 1 month separated the respective seedlings in reaching this threshold late summer. About 20 percent (n = 4) of the 0.5-N seedlings emerged from the grass stage; the average height of this treatment was 7.7 cm. About 60 percent (n = 11) of the seedlings in the 2.0-N treatment left the grass stage; average height was 11.8 cm. In the 4.0-N treatment, 65 percent (n = 13) of the seedlings were taller than 10 cm; the average height was 13.7 cm.

The development of seedlings from the 0.5-N, 2.0-N, and 4.0-N treatments are illustrated in figure 3. After 2 years, the buds of the 0.5-N treatment remained in the grass stage and were in the "round' stage of development. Although "elongated" buds were present in both the 2.0-N and 4.0-N treatments, the 4.0-N seedlings more in a more advanced stage. The photo record of bud development indicated that they were in the elongated stage with white bud scales when they reached 25 mm in RCD.

When RCDs at outplanting were regressed to those 2 years after planting for each seedling in each fertilizer treatment, a negative relationship developed with the 4.0-N levels (fig. 4). This was unexpected and prompted further examination of the data. Changes in seedling RCD growth between measurement periods indicated the 4.0-N seedlings grew more than the others during the first year after outplanting (table 2), but during the second year incremental growth was less than that for the 2.0-N treatment and no better than the 0.5-N treatment. So,

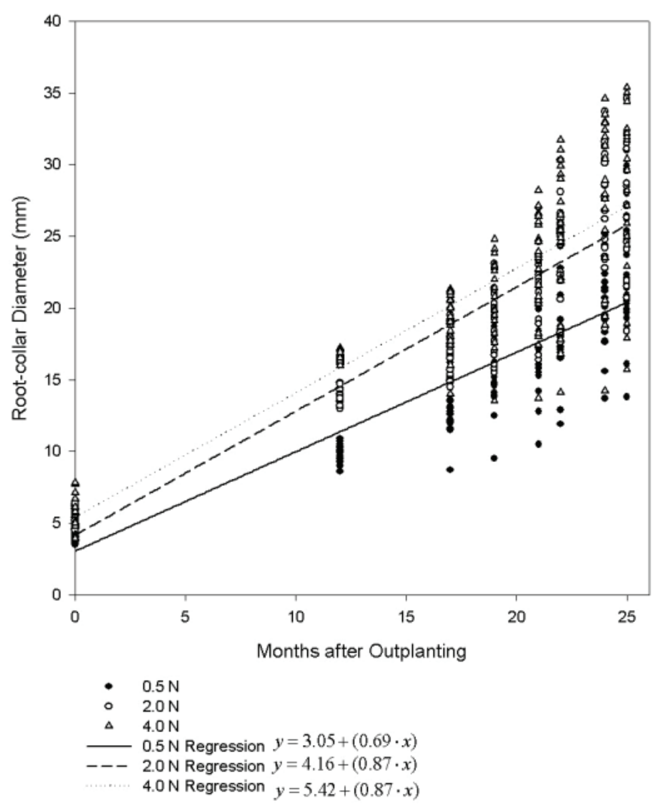

Figure 1—Root-collar diameter growth over a 2-year period of seedlings fertilized in the nursery with 0.5, 2.0, and 4.0 mg of nitrogen per seedling.

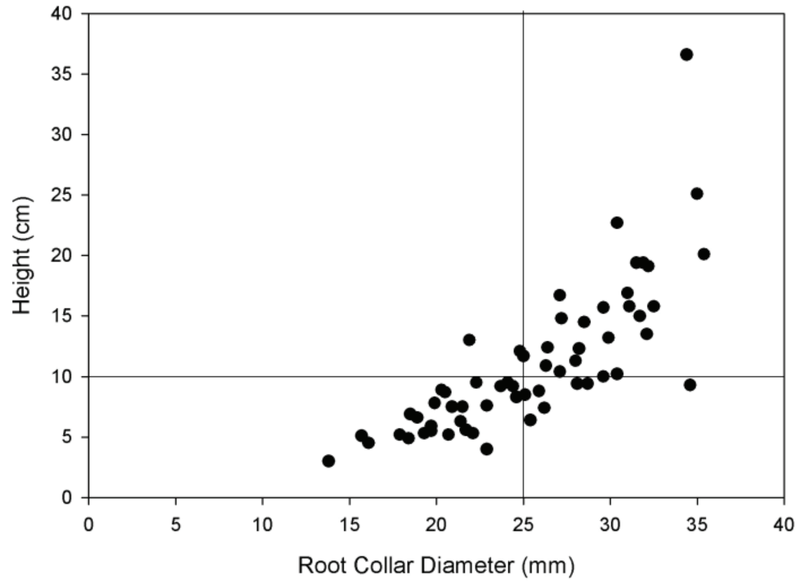

Figure 2—Relationship of longleaf pine seedling height to root-collar diameter. The lines at 10 cm height and 25 mm root-collar diameter indicate emergence from the grass stage into height growth.

Figure 3—Average bud development after 2 years in seedlings representing 0.5 N (left), 2.0 N (center), and 4.0 N (right). Seedlings in the 0.5 N treatment remained in the grass stage and were characterized by a round bud. Seedlings in both the 2.0 N and 4.0 N treatments were in the elongated stage and entering height growth. They exhibited white scaled bud formation.

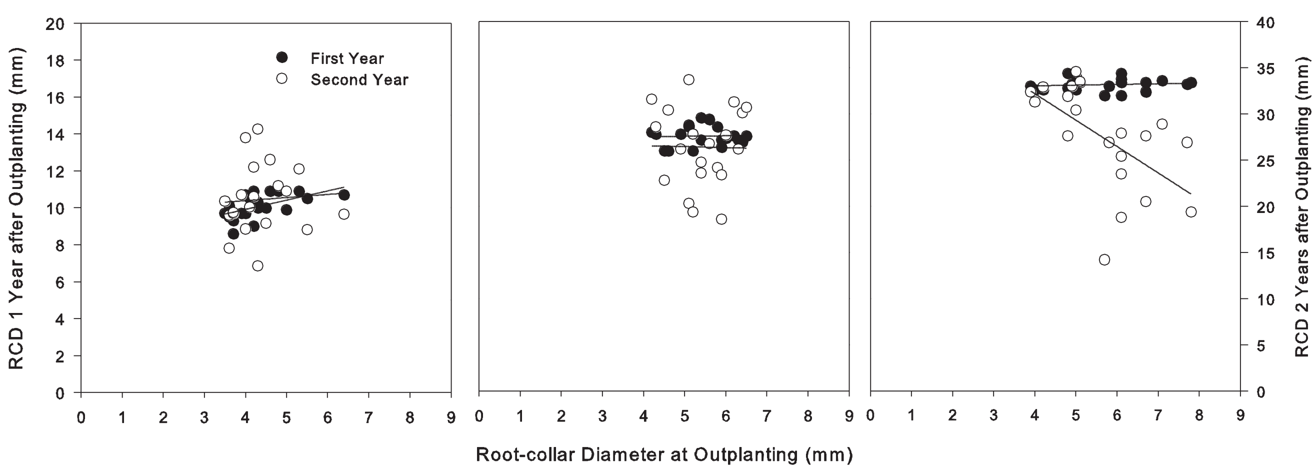

Figure 4—Average RCD increments of 0.5 N (left), 2.0 N (center) and 4.0 N (right) fertilization rates after 1 and 2 years are regressed with RCD at outplanting. The negative slope of incremental growth of the larger seedlings in the 4.0 N treatments during year two was unexpected and merits further experimentation.

Table 1—Average root-collar diameters (mm) of longleaf pine seedlings following planting by date and nutrient treatments

Treatment[a]	11/16/04	11/15/05	4/12/06	6/27/06	8/8/06	9/22/06	10/31/06	12/11/06
0.5 N	4.4	10.1	13.5	15.4	16.9	18.7	20.9	21.7
2.0 N	5.3	13.8	17.1	19.2	21.5	24.1	26.4	25.7
4.0 N	5.7	16.6	19.1	20.9	22.7	24.9	26.7	26.6

[a]Treatments represent applications of mg nitrogen (N) per seedling per week for 20 weeks and at 28 and 32 weeks.

Table 2—Changes in seedling root-collar diameter (mm) growth between measurement periods

Treatment[a]	11/16/04	11/15/05	4/12/06	6/27/06	8/8/06	9/22/06	1/31/06	12/11/06
0.5 N	--	5.7	3.4	1.9	1.5	1.8	2.2	0.8
2.0 N	--	8.5	3.3	2.1	2.3	2.6	2.3	-0.7
4.0 N	--	10.9	2.5	1.8	1.8	2.2	1.8	-0.1

[a]Treatments represent applications of mg nitrogen (N) per seedling per week for 20 weeks and at 28 and 32 weeks.

although early growth of the 4.0-N-treatment seedlings was good, these high, positive rates of incremental growth were not maintained during the second year.

DISCUSSION

For the entire population measured in this study (all treatments combined), we confirmed the relationship between RCDs of 25 mm (1 inch) and heights of 10 cm (4 inches) that Wahlenberg (1946) and others established as the criteria for emergence of longleaf pine seedlings from the grass stage (fig. 1). RCD increased after outplanting, with the largest RCDs found in the two highest fertilization treatments (fig. 1, table 1). Moreover, the two highest fertilizers rates (2.0 and 4.0) allowed 2.5 and 3.25 times more seedlings, respectively, to exit the grass stage than the 0.5-N rate.

The three treatments in this evaluation represented the lowest, mid-range, and highest rates of nitrogen application in the Jackson and others (2006, 2007) study. It appears that the 0.5-N rate fails to provide sufficient nutrition to produce seedling quality that performs well (in terms of RCD growth and therefore, emergence from the grass stage) in the field. The 2.0-N application rate resulted in excellent RCD growth, corresponding bud development, and seedlings that exited the grass stage during the second year after outplanting. The 2.0-N treatment was very similar to the 4.0 N treatment in terms of second-year RCD (25.7 vs. 26.6 mm), height (11.8 vs. 13.7 cm), and percentage of seedlings emerging from the grass stage (60 vs. 65 percent), despite the fact that the 4.0-N seedlings received twice as much fertilizer in the nursery. We did observe a negative correlation in the 4.0-N-treatment, but not in original RCD and second-year RCD in the 2.0-N.

Although this is a small data set, it raises the question about the effects of aggressive root growth in small container cavities. Too much root growth can cause binding and may reflect seedlings staying too long in the containers or the application of excessive fertilizers that result in seedlings too large for the container. Lamhamedi and others (1996) suggested that excessive root growth of black spruce (*Picea mariana* [Mill.] B.S.P.) seedlings in the root plug can lead to low root quality and therefore increased susceptibility to water stress in spite of an apparently favorable shoot-to-root ratio. Their results point toward reduced root hydrological function rather than more vigorous shoot growth as the cause. South and others (2004) were able to relate decreases in container longleaf pine seedling survival to root binding in the root plug. They calculated a root bound index (RBI) by dividing seedlings' RCD by cell cavity diameter; a RBI ≥ 30 percent was associated with higher mortality. Using this critical RBI value and our container that had a 38 mm cavity diameter, seedlings having a RCD ≥ 11.4 mm should experience higher mortality rates. It stands to reason that one should probably observe a decrease in overall seedling growth at a level less than that associated with mortality; South and others (1996) did not discuss this. In our study, however, such a relationship is not clear. For instance, in the 4.0-N treatment, seven of the ten seedlings having the largest RCDs at outplanting did not exit the grass stage, but their RBI values ranged from just 15 to 20.5 percent (RCDs ranged from 5.7 to 7.8 mm), values well below the 30 percent value of South and others (2004). The three that did grow out of the grass stage had RBIs of 16 percent (6.1 mm) to 19 percent (7.1 mm). Moreover, in the 2.0-N-treatment, of the eight seedlings with RCDs between 5.7 and 6.5, four of them exited the grass stage (5.8 to 6.0 mm RCD).

During container nursery production, applications of higher rates of N usually promote shoot growth and discourage root growth, whereas low N applications favor root growth. In the Jackson and others (2006) study, root growth between 20 and 30 weeks, when only two fertilizer applications occurred, increased 138 percent for the 4.0 N treatment compared to 69 and 88 percent for the 0.5-N and 2.0-N treatments. Unfortunately, we do not have the data to attempt to correlate root biomass and RCD, but it is quite likely that RBI may be better defined by a covariant analysis of these two variables on outplanting performance, rather than simply RCD.

So, this study is a bit of a conundrum. When looking at the population of seedlings fertilized with 4.0-N, they average the largest RCD, the tallest heights, and the largest number emerging from the grass stage. When looking at individual seedlings within that population, however, it appears that seedlings with the greatest initial RCDs are not performing as well. Although this could be a reflection of “bound roots” it could also be a function of other factors, in particular, genetics. For example, in western white pine (*Pinus monticola* Dougl. ex D. Don), seed dormancy of individual families is highly hereditable, and thought to be an adapted mechanism to extend successful germination of the species across more environmental conditions (Hoff 1987). Perhaps emergence from the grass stage is also highly heritable from a family standpoint, allowing a portion of an individual family to emerge from the grass stage (or remain in the grass stage) as a strategy against untimely environmental conditions. Because our longleaf was a wild-collected source comprised of various families, we cannot discern that. Nor can we confidently state that this is not a measurement artifact that may disappear in subsequent growing seasons as we continue to monitor the seedlings.

We have insufficient data to establish a rational for what appears to be a trend of poor RCD growth of longleaf seedlings during the second year after having been fertilized in the greenhouse at a high 4.0-mg-N/seedling rate. We have an additional study in progress now that may shed some additional insight into this phenomenon. If root binding has a negative effect on growth after establishment, however, many container cultural treatments need to be reevaluated. Over 50 million longleaf pine seedlings are grown annually in containers throughout the South. Further evaluations of this phenomenon of reduced growth during the second year after outplanting are needed to assure that the best quality planting stock is being used in these reforestation practices.

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EFFECTS OF CONTAINER CAVITY SIZE AND COPPER COATING ON FIELD PERFORMANCE OF CONTAINER-GROWN LONGLEAF PINE SEEDLINGS

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Abstract—Longleaf pine (*Pinus palustris* Mill.) seedlings were grown for 27 weeks in 3 container cavity sizes [small (S), medium (M), and large (L)], and half the containers were coated with copper (Cu). In November 2004, we planted 144 seedlings from each of 6 container treatments in each of 4 replications in central LA. All plots were burned in February 2006. Cavity size or Cu had no effect on seedling survival after one growing season in field. Small seedlings had a lower survival rate than either M or L seedlings from May through November of the second growing season; and Cu did not affect seedling survival the second year. Seedlings of all treatments had 88 to 98 percent survival after 2 years. More than 40 percent of the Cu-L and L seedlings had heights exceeding 12 cm and were considered coming out of the grass stage, whereas fewer than 5 percent of the Cu-S and S seedlings were coming out of the grass stage. Season, but not container treatments, affected photosynthetic rates and chlorophyll contents.

INTRODUCTION

Extensive harvest of longleaf pine (*Pinus palustris* Mill.; LLP) for timber and naval store products between the late 1800s and early 1900s, conversion of lands that had supported LLP to agricultural uses or to plantations of other fast-growing pine species, and exclusion of fire from the landscape, all contributed to the disappearance of about 96 percent of the pre-European settlement LLP ecosystems in the South (Brockway and Outcalt 1998, Landers and others 1995, Outcalt 2000). For the last two decades, many public, industrial, and private land managers and owners have been actively restoring LLP ecosystems in the Southern United States (Barnett 2002, Boyer 1989, Lander and others 1995). In most of the artificial LLP regeneration efforts, the planting of container-grown LLP seedlings usually has had a higher survival rate than bare-root stock plantings (South and others 2005 and references cited therein). However, one noted drawback of using container-grown stock for planting is that the established plantings have some sapling toppling in strong wind (South and others 2001). Other seedling qualities of container-grown LLP may also contribute to planting failure. For example, the root-bound index, the ratio of seedling ground-line diameter to container cavity top diameter, has been used to predict field survival and performance of container-grown seedlings (South and others 2005). Root-bound indices of greater than 28 percent have been associated with poor survival of LLP two years after planting (South and others 2005).

Improvements in the morphological quality of container stock root systems have been attempted by adding ridges to the cavity or coating it with copper (Cu). Cavity ridges help reduce root spiraling by training primary lateral roots to grow vertically (Barnett and Brissette 1986). Slow release of low-concentration Cu stops seedling lateral roots from elongating when they reach the cavity wall (Ruehle 1985). In a root growth potential test, LLP seedlings grown in Cu containers produced more new roots than those grown in non-Cu containers or bareroot seedlings (South and others 2005). Lodgepole pine (*P. contorta* Dougl.) grown in Cu-coated containers had fewer leaning seedlings three years after planting than those from non-Cu containers (Krasowski 2003).

In 2004, a study comparing the effects of different container cavity sizes and Cu coating on LLP seedling growth, field performance, and tree stability was begun in central LA. This report concentrates on the field performance of planted LLP seedlings for two growing seasons. Specifically, we assessed seedling survival, height growth, photosynthetic rate, and chlorophyll (Chl) content.

MATERIALS AND METHODS

Seedling Culture

Longleaf pine seeds from a Florida seed orchard mix were sown in containers in April 2004. There were six container treatments: three cavity sizes and two (with and without Cu) cavity coating treatments. Cavity top diameter (cm)/depth (cm)/volume (ml) for the small (S), medium (M) and large (L) cavity sizes were 2.8/13.3/60, 3.5/14.9/93, and 4.2/15.2/170, respectively. Cavity numbers per m^2 for S, M, and L containers were 756, 530, and 364, respectively. Styroblock ® and Copperblock® containers (Beaver Plastics Ltd, Edmonton, Alberta, Canada) of these cavity dimensions were used for no Cu and Cu-coating treatments. Copper oxychloride is the coating's active ingredient. Approximately 700 LLP seedlings were grown for each of the 6 container treatments.

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We adapted protocols for growing LLP that were established by Barnett and McGilvray (1997, 2000) for this study. Specifically, the growth medium was a 1:2 mixture of commercial peat moss and vermiculite. The growth medium contained Osmocote® 19-6-12 slow release fertilizer (The Scotts Miracle Grow Company, Marysville, OH) at a rate of 3.6 kg/m^3. Between mid-May and the end of September 2004, we applied a 0.05- to 0.06-percent solution of water soluble fertilizer (Peters Professional® 20-19-18, J. R. Peters Inc., Allentown, PA) weekly until root plugs were saturated. Between July and mid-October 2004, Benlate® fungicide (Dupont, Wilmington, DE) was applied twice monthly. We watered the seedlings as needed. Seedlings were grown for 27 weeks under ambient light in a greenhouse where air temperature was maintained at 20 to 25 °C. Six weeks before planting, fertilization was stopped and watering was reduced to encourage bud set. All needles were trimmed to 15 to 20 cm two weeks before lifting.

Field Experiment

Study site—Our study is located on the Palustris Experimental Forest within the Kisatchie National Forest in Rapides Parish of central LA (31°11'N, 92°41'W). The soil is a moderately well-drained, gently sloping Beauregard silt loam (fine silty, siliceous, thermic, Plinthaquic Paludults). Mima mounds of Malbis fine sandy loam (fine loamy, siliceous, thermic, Plinthic Paleudults) are scattered across the study area. The dominant vegetation before we established the study was composed of grasses and forbs. In May 2004 we prepared the site for planting by broadcast application of a tank mixture of glyphosate and triclopyr herbicides. Two weeks later, the area was rotary mowed.

Experimental design—We established the field study using a randomized complete block design with four replications. In summer 2004, 24 treatment plots of 0.0576 ha (24 by 24 m) each, were established in the 3.5-ha site. Treatment plots were blocked based on apparent soil drainage using depth-to-mottles and plot concavity or convexity as indicators of drainage. Seedlings grown in the six cavity treatments (S, Cu-S, M, Cu-M, L, and Cu-L) were randomly assigned to a plot in each block.

Plantation establishment—In early November 2004, 27 week old container-grown LLP seedlings were lifted and planted on the same day. We planted seedlings at 2 by 2 m spacing using a planting punch customized for each of the three cavity dimensions. Treatment plots are 12 rows of 12 trees. All plots were burned in February 2006 as part of the routine management of the site. By August 2006, all LLP seedlings grew new needles, and ground-cover vegetation returned to the site.

Field and Laboratory Measurements

In November 2005, we surveyed all seedlings for survival in each plot, as well as in May, July, September, and November 2006. Seedling height growth was measured on the interior 64 (8 rows of 8 seedlings) seedlings in December 2005 and 2006. Seedlings taller than 12 cm were considered as growing out of the grass stage (Haywood 2000).

In July 2006, three seedlings from each of the 24 plots were randomly selected and tagged for long-term measurements of photosynthetic rate and Chl content. We measured photosynthesis rate using a LiCor 6400 portable, open-system infrared gas analyzer (LiCor, Lincoln, NE). Photosynthetic active radiation was set between 1400 and 1600 µE/m^2/sec with a red-blue light source inside the measuring chamber (3 by 2 cm); and the CO_2 level for the reference chamber was set at 400 ppm. The middle sections of two three-needle fascicles were enclosed in the photosynthesis chamber during measurements. After measurements, we harvested those fascicles, stored them on ice, and transported them to the laboratory for needle surface area measurement and Chl analysis.

Needle sections of 6 to 8 cm in length, including the parts (3 cm length) that were measured for photosynthesis, were measured for surface area using the displacement method devised by Johnson (1984). Next, these needle sections were cut into segments of 0.2 to 0.3 cm. Needle segments were extracted for Chl a and Chl b using N, N'-dimethylformamide (DMF) (Moran and Porath 1980). No tissue grinding was involved with this protocol. Culture tubes containing DMF and needle segments were placed in the refrigerator until the segments lost all color. Absorbance of the DMF extract was read at 664 nm and 647 nm by a DU-70 spectrophotometer (Beckman Coulter Inc., Fullerton, CA). Contents of Chl a and Chl b were calculated using the simultaneous equations of Porra and others (1989).

Statistical Analysis

Percentages for survival and seedlings out of the grass stage were arcsine transformed [arcsin (percent square root)] before analysis (Steel and Torrie 1980). The transformed survival percentages were compared for the October 2005, May, July, September, and November 2006 measurement dates using a repeated measures randomized complete block design model (α=0.05) (SAS Institute 1991). In the analysis, Cu (yes and no) and container size (large, medium, and small) were the two treatment levels, and we tested for copper x container-size interactions. Survival was also compared by date using a randomized complete block design model, and if significant treatment effects were found, plot mean comparisons were made with Duncan Multiple Range Tests (α=0.05). Likewise, we compared seedling heights after the first (October 2005) and second (November 2006) growing seasons and the percentage of seedlings out of the grass stage (greater than 12 cm tall) after the second growing season. Photosynthesis rate and Chl a + b content of longleaf pine seedlings were compared for the July, October, November, and December 2006 measurements, in addition to comparisons of container size and Cu coating across all months.

RESULTS AND DISCUSSION

Seedling Survival

There were no cavity size and Cu coating interactions for seedling survival of either year. Cavity sizes and Cu coating had no effect on LLP seedling field survival after one growing season (table 1). The trend was repeated for Cu coating during the second growing season. Seedlings grown in S

Table 1—Effects of container cavity size and copper coating on the first and the second year field survival of longleaf pine seedlings. There was not size and copper coating interaction for either year. Seedlings were grown in containers for 27 weeks and then planted in central LA in November 2004

Treatment	Oct-05	May-06	Jul-06	Sep-06	Nov-06
			Seedling survival, percent		
Container size					
Large	98.3a[a]	97.1a	96.9a	96.9a	96.9a
Medium	98.5a	96.4a	96.4a	96.4a	96.4a
Small	97.1a	91.4b	90.6b	90.6b	90.5b
			Seedling survival, percent		
Copper coating					
Yes	98.9a	96.3a	96.0a	96.0a	95.9a
No	97.0a	93.6a	93.3a	93.3a	93.3a

[a]Least square means within the same column followed by the same letter were not significantly different at the 0.05 level.

containers had lower survival than those grown in M or L containers for all measurement months during the second growing season (table 1). Between November 2005 and May 2006, S and Cu-S treatments lost quite a few seedlings (fig. 1). This mortality might be associated with the prescribed fire conducted on the study in February 2006. After May 2006, there was hardly any mortality in any treatment (table 1, fig. 1). Overall survival for LLP seedlings of all treatments ranged between 88 and 98 percent 2 years after planting. This rate of survival was as good as in the study by Haywood (2000) and better than values reported by others (Boyer 1989, Ramsey and others 2003, Rodriguez-Trejo and others 2003, South and others 2005).

Seedling Growth

The Cu-L seedlings were shorter than the L seedlings one year after planting (fig. 2). This trend was reversed two years after planting. In either year, Cu coating did not affect height growth of cavity size M or S. Seedlings grown in S and Cu-S containers were the shortest in both growing seasons (fig. 2). One of the reasons for LLP regeneration failure has been that some LLP seedlings remain in the grass stage for several years (Haywood 2000, South and others 2005). Typically, such seedlings were shaded by herbaceous and woody vegetation, and therefore more prone to infection by brown-spot needle blight (*Mycosphaerella dearnessii* M.E. Barr.). In our study, the percentage of seedlings growing out of the grass stage after two growing seasons was positively associated with container cavity size (fig. 3). However, Cu coating did not affect the percentage of seedlings growing out of the grass stage (fig. 3). Weed control may shorten the time

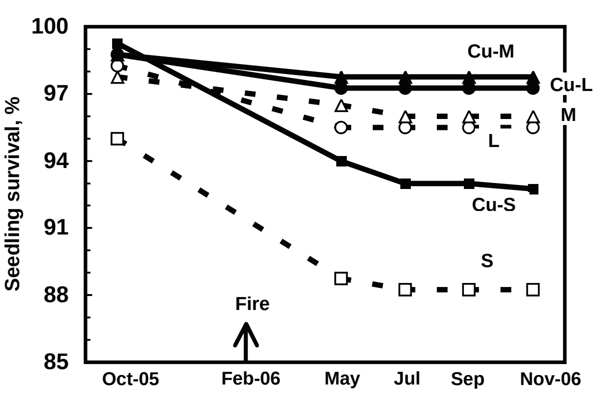

Figure 1—Effects of container cavity size and copper (Cu) coating on longleaf pine seedling field survival for two growing seasons after planting. Seedlings were grown in containers for 27 weeks in a greenhouse and planted in central LA in November 2004. Treatments were: Cu-L: large size cavity with Cu coating; L: large size cavity; Cu-M: medium size cavity with Cu coating; M: medium size cavity; Cu-S: small size cavity with Cu coating; and S: small size cavity. Arrow indicates when the study area was burned.

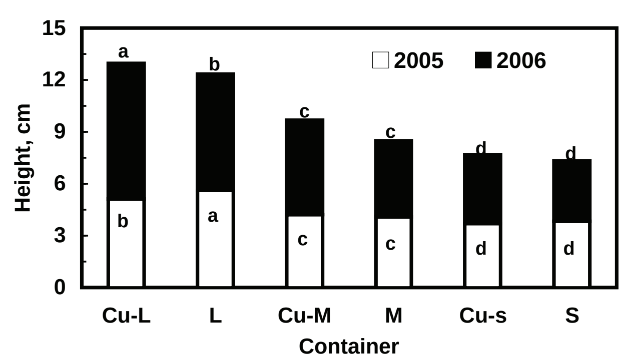

Figure 2—Effects of container cavity size and copper coating on longleaf pine seedling height growth in the field at the end of the first (2005) and second (2006) growing seasons. Seedlings were grown in containers for 27 weeks in a greenhouse and planted in central LA in November 2004. Treatments were: Cu-L: large size cavity with Cu coating; L: large size cavity; Cu-M: medium size cavity with Cu coating; M: medium size cavity; Cu-S: small size cavity with Cu coating; and S: small size cavity. Least square means with the same letter for each year were not significantly different at the 0.05 level.

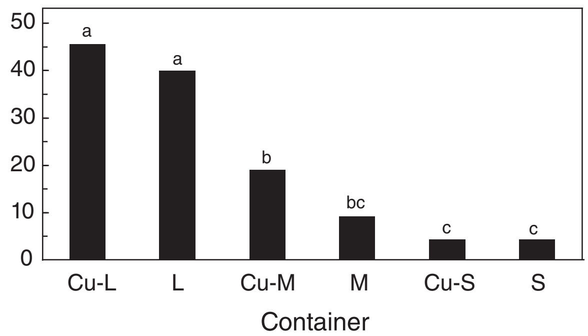

Figure 3—Effects of container cavity size and copper coating on percentage of longleaf pine seedlings growing out of the grass stage at the end of the second growing season. Seedlings were grown in containers for 27 weeks in a greenhouse and planted in central LA in November 2004. Treatments were: Cu-L: large size cavity with Cu coating; L: large size cavity; Cu-M: medium size cavity with Cu coating; M: medium size cavity; Cu-S: small size cavity with Cu coating; and S: small size cavity. Least square means with the same letter were not significantly different at the 0.05 level.

the LLP seedlings remaining in the grass stage (Haywood 2000, Ramsey and others 2003). Planting LLP grown in large containers should be considered an option for shortening the time seedlings remain in the grass stage.

Physiological Attributes

Photosynthetic rates we measured (table 2) were within ranges similar to rates measured in a greenhouse study of LLP by Jose and others (2003). The S seedlings in our study had a slightly lower photosynthetic rate than seedlings of the other five treatments (data not shown). Container treatment did not affect seedling Chl a+b contents (data not shown). Season, however, had significant but different effects on photosynthetic rate and Chl a+b content (table 2).

For the month of July, with excessively high temperatures and dry conditions, the photosynthesis rate was lower than in October (table 2). In a loblolly pine (*P. taeda* L.) study located near our study, photosynthetic rates for July and August were much lower than those measured in October and November (Tang and others 1999). Further, the needles sampled in July had lower Chl a+b than those measured in October and November (table 2). Because all plots were burned in February 2006, needles sampled in July, although similar in length to those sampled in the other months, might not have been physiologically mature. The lower Chl a+b content will also affect negatively the photosynthetic rate as shown here between July and October measurements.

Mean ambient temperatures during photosynthesis measurements in November and December were 14 °C and 19 °C, respectively. Such temperatures in central LA were lower and higher than mean day temperatures for November and December, respectively. Although the December needles had only 56 percent of the November Chl a+b level, their photosynthetic rate was 92 percent of that in November needles (table 2). Temperatures apparently are very critical during photosynthesis measurements in the winter season.

Table 2—Photosynthetic rate and chlorophyll a + b content (Chl) of longleaf pine seedlings in 2006. Seedlings were grown in containers for 27 weeks and then planted in central LA in November 2004

Month	Photosynthetic rate	Chlorophyll a+b content
	$\mu mol/m^2/sec^1$	$nmol/cm^2$
Jul	5.80b[a]	15.50c
Oct	7.17a	20.63b
Nov	5.06c	25.55a
Dec	4.66d	14.48d

[a]Least square means within the column followed by the same letter were not significantly different at the 0.05 level.

Decreased levels of Chl a+b in December needles were typical of most coniferous needles in winter (Kostner and others 1990). Nevertheless, with such active photosynthesis in December when day time temperatures are in the high teens, LLP in this area can continue its growth in these winter months when rainfall is ample and competing vegetation is dormant.

PRACTICAL APPLICATIONS

For artificial LLP regeneration using container stock, it is recommended that seedlings be grown in container cavity of at least 98 ml (Barnett and McGilvray 1997), a little larger than the M containers used in this study. The extra cost of growing seedlings in M containers rather than the S containers can be justified by the greater survival and accelerated height growth of M stock. Of course, it is up to the land managers whether they want to invest in LLP seedling stock grown in L containers. On sites where vegetation competition is severe, taller seedlings growing out of the grass stage will be less shaded by competition and become more tolerant of fire. Greater than 40 percent (versus 9 to 19 percent) of seedlings growing out of the grass stage for L and M seedlings, respectively, might justify the extra cost.

Although the advantage of Cu coating on early seedling field performance was not definitive in our study results, we believe that more evenly distributed root systems along the length and circumference of the root plug of longleaf pine seedlings grown in Cu cavities (Mary Anne Sword Sayer, personal observation) will enable them to perform better when there is a severe drought or when strong wind threatens to topple LLP saplings.

CONCLUSIONS

When care was taken for growing and planting LLP seedlings, even those grown in small cavity size containers had 88 percent survival two years after planting. Mean height growth and number of seedlings growing out of the grass stage increased with container cavity size. Container size and Cu coating did not affect photosynthesis rate or chlorophyll content. Our study showed that photosynthesis was still active in winter months. We will be monitoring this study continuously for some physiological attributes and, later, for morphological attributes such as sapling root system architecture and stability.

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ARTIFICIALLY REGENERATING LONGLEAF PINE ON WET SITES: PRELIMINARY ANALYSIS OF EFFECTS OF SITE PREPARATION TREATMENTS ON EARLY SURVIVAL AND GROWTH

Benjamin O. Knapp, G. Geoff Wang, and Joan L. Walker[1]

Abstract—Our study, conducted over two years on poorly drained, sandy sites in Onslow County, NC, compared the effects of eight common site preparation treatments on early survival and growth of planted longleaf pine seedlings. Through two growing seasons, we found survival to be similar across all treatments ($p = 0.8806$), but root collar diameter was greatest with combinations of mounding and herbicides or bedding and herbicides ($p < 0.0001$). After the first growing season, treatments that included herbicides resulted in the greatest reduction in abundance of surrounding vegetation ($p < 0.0001$), but by the second growing season mounding treatments provided the best vegetation control ($p < 0.0001$). Mounding and bedding treatments reduced soil moisture when compared to flat planting in both growing seasons ($p < 0.0001$). When used properly, site preparation treatments that reduce competition from surrounding vegetation and relieve excess soil moisture will help improve early growth rates of artificially regenerated longleaf pine on wet sites.

INTRODUCTION

Restoration of the longleaf pine (*Pinus palustris*) ecosystem is an important topic for landowners within the Southeastern United States. The natural range of longleaf pine once dominated the Atlantic coastal plain and included sites that ranged from well drained sandhills to poorly drained flatwoods (Boyer 1990). However, historic land use and forest management practices that included fire exclusion have resulted in widespread conversion of longleaf pine sites to other forest types. Many landowners now interested in restoring longleaf pine are faced with the problem of successful seedling establishment, especially on wet sites that support an abundance of competing vegetation.

Although longleaf pine may be established using natural regeneration methods (Croker and Boyer 1975), artificial regeneration must be used in areas that no longer contain mature pines in the overstory to provide seed (Barnett 1999). Longleaf pine is considered intolerant of competition for available resources (Boyer 1990, Wahlenburg 1946) and therefore thrives in the absence of canopy trees. Following conventional southern silviculture, regeneration protocols would include removal of canopy trees and implementation of site preparation techniques to improve growing conditions for planted longleaf pine seedlings.

Common site preparation techniques of this region include mechanical treatments, chemical applications, and prescribed fire. Of these, prescribed fire is considered an essential ecological process shaping the structure and function of the longleaf pine ecosystem (Landers and others 1995), and periodic fire is a necessary occurrence for good seedling establishment. However, mechanical or chemical treatments may also be used to promote early seedling growth or survival by reducing competing vegetation and alleviating limiting growth conditions (Boyer 1988, Croker and Boyer 1975), and the use of mechanical treatments has been shown to be critical in the absence of prescribed fire (Croker 1975).

Poorly drained sites of the coastal plain present unique problems for land owners regenerating longleaf pine. First, because wet sites are typically highly productive, competitive pressures are high. The development of effective herbicides has provided opportunities for competition control through chemical application, and previous work has found herbicides to benefit longleaf pine seedling establishment when used alone (Nelson and others 1982) or in combination with mechanical treatments (Boyer 1988). Second, excess moisture has been reported as a limiting factor in southern pine seedling growth. Previous studies on loblolly pine (*Pinus taeda*) and slash pine (Pinus elliottii) suggest that mechanical treatments such as bedding and mounding result in greater seedling growth by increasing soil drainage and raising the root zone above the water table (Haywood 1987, Outcalt 1984, Pritchett 1979). However, it is not clear whether longleaf pine seedlings will exhibit a similar response to mechanical treatments on wet sites.

This study was designed to evaluate the effectiveness of various site preparation treatments used for regenerating longleaf pine seedlings on wet sites. We attempted to explore the influence of surrounding vegetation abundance and soil moisture on seedling response. Our specific objectives were to: 1) determine the effects of site preparation treatments on longleaf pine seedlings survival and growth and 2) quantify effects of site preparation treatments on surrounding vegetation and soil moisture. To fully understand the mechanisms behind seedling response to site-preparation, a more complete analysis of the effects of site preparation on resource availability is planned.

METHODS AND MATERIALS

Study Site

This study was conducted on Marine Corps Base Camp Lejeune, in Onslow County, NC, within the Atlantic Coastal Flatlands Section of the Outer Coastal Plains Mixed Forest Province (Bailey 1995). All study sites are on Leon fine sand,

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a Spodosols with light gray to white sand in the first 30 to 60 cm and a dark B horizon of organic accumulation. A hardpan beneath the surface impedes internal drainage and creates poorly to very poorly drained conditions. Historically, these sites were wet longleaf pine savannas and consisted of longleaf pine overstories with herbaceous ground layers dominated by grasses (e.g. Aristida spp., Andropogon spp., Schizachyrium spp.), sedges, and a diverse mix of forbs.

Experimental Design

The study was a randomized complete block design, with eight treatments replicated on five blocks. Each experimental unit was 0.6-ha and included a 0.4-ha measurement unit. Treatment application included two types of site preparation: treatments designed to control competing vegetation (chopping or herbicides) and treatments that impact soil drainage (flat planting [no treatment], mounding, or bedding). The eight treatments of this study were various combinations of these site preparations, and included a check (F), chopping and flat planting (CF), herbicide and flat planting (HF), chopping and mounding (CM), herbicide and mounding (HM), chopping and bedding (CB), herbicide and bedding (HB), and chopping, herbicide, and bedding (CHB).

Prior to treatment application, all canopy trees were removed and remaining vegetation was sheared. Vegetation control treatments (chopping or herbicides) were applied to each experimental unit first, followed by the appropriate planting-site treatment. Chopping was done with a 2.4-m drum chopper pulled by a crawler tractor (Cohen and Walker 2005). The herbicide treatment, made up of 0.70 kg/ha of imazapyr and 0.56 kg/ha triclopyr, was broadcast at a rate of 280 L/ha. Mounds approximately 1.2-m-wide were created with an excavator and placed in rows as opposed to random distribution typically associated with mounding preparation. We used a 6-disc bedding harrow to create 2.1- to 2.4-m-wide beds. Treatment application was complete in August 2003. All study sites were burned following treatment application to further prepare them for planting. In December 2003, container-grown seedlings from locally collected seed were hand planted at 4.5 m by 2 m spacing.

Data Collection

A sub-sample of 45 seedlings was randomly selected and permanently marked for measurement on each experimental unit. Seedling growth was monitored by measuring the diameter of the root collar with digital calipers. Survival was determined by monitoring mortality within the subsample of seedlings.

Of the 45 seedlings measured for seedling response data, we randomly selected 15 to determine abundance of surrounding vegetation. An approximately 1 m2 circular plot was centered at each selected seedling, and an ocular estimate of the percentage of the ground surface covered by vegetation was recorded. Cover classes were modified from the North Carolina Vegetation Survey (Peet and others 1998), as follows: (1) < 1, (2) 1 to 2, (3) 3 to 5, (4) 6 to 10, (5) 11 to 25, (6) 26 to 50, (7) 51 to 75, (8) 76 to 90, (9) 91 to 100 percent.

Percent soil moisture was measured at a 6-cm depth using a Theta Probe Moisture Meter (Delta-T Devices, Ltd.). Measurements were taken adjacent to 10 seedlings from each sub-sample per experimental unit. To reduce variability from weather conditions, all measurements within a single block were taken from 13:00 to 15:00. No measurements were taken within 24 hours of a precipitation event.

Data Analysis

We used one-way analysis of variance (ANOVA) to determine differences among the treatments for the seedling response variables (survival, growth), total vegetation abundance, and soil moisture. Significant differences among the treatments were determined using Tukey's LSD post-hoc test. Transformations were used to normalize data if necessary, and we used a level of significance of $\alpha = 0.05$.

RESULTS

Seedling Response

Seedling survival at the end of the first and second growing seasons was not affected by the site preparations (p = 0.5557, p = 0.8806, respectively) (fig 1). In 2004, survival ranged from 67.7 to 76.8 percent, with a mean of 72.5 percent. By the end of the second growing season, mean survival dropped to 59.1 percent and ranged from 57.1 to 64.5 percent. We found significant differences in root collar diameter among the various site preparation treatments in both 2004 (p = 0.0032) and 2005 (p < 0.0001) (fig 2). In 2004, there was a relatively narrow range of diameters, from 11.7 mm on CF to 13.4 mm on CHB. The check (F) and the chop treatment (CF) were significantly smaller than all other treatments. In 2005, growth differences were more pronounced. The check and CF remained the smallest among the treatments, with the greatest growth on CHB, HB, and HM. A more complete analysis of the effect of site preparation treatments on seedling response is presented in Knapp and others (2006).

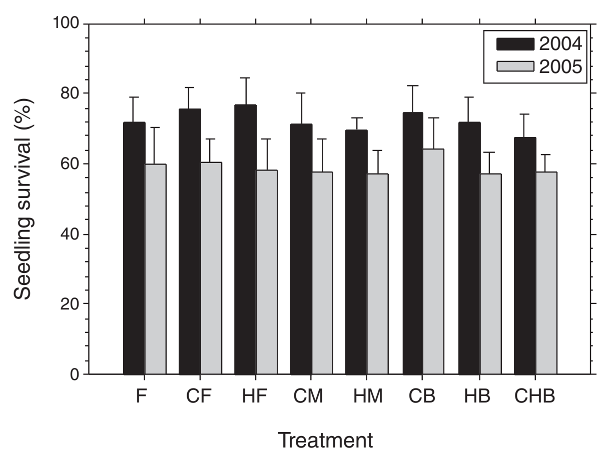

Figure 1—Seedling survival (%) through August 2004 and August 2005 for each treatment. Survival was not significantly different by treatment for either year (p = 0.5557, p = 0.8806, respectively). Error bars are one standard error. F = flat (check), CF = chop/flat, HF = herbicide/flat, CM = chop/mound, HM = herbicide/mound, CB = chop/bed, HB = herbicide/bed, CHB = chop/herbicide/bed.

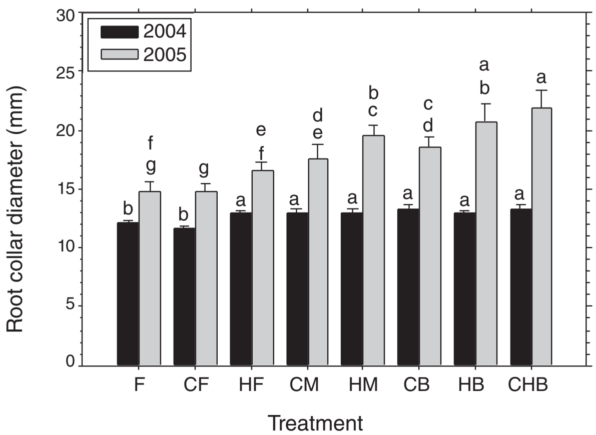

Figure 2—Mean root collar diameter (mm) in August 2004 and August 2005 for each treatment. Similar letters within a year indicate no significant difference. Error bars are one standard error. F = flat (check), CF = chop/flat, HF = herbicide/flat, CM = chop/mound, HM = herbicide/mound, CB = chop/bed, HB = herbicide/bed, CHB = chop/herbicide/bed.

Vegetation Cover

The treatments used in the study significantly affected the abundance of surrounding vegetation in both growing seasons (2004: $p < 0.0001$, 2005: $p < 0.0001$) (fig 3). In 2004, percent cover was highest on F, although not significantly different from CF. All other treatments reduced vegetation abundance to below 30 percent cover, although treatments with the least vegetation present included HM, HB, and CHB. Cover on F and CF remained the highest in 2005, followed by HF, CB, HB, and CHB. The lowest abundance of surrounding vegetation two years after treatment application was on HM and CM.

Soil Moisture

In 2004, there was significantly more soil moisture ($p < 0.0001$) present on HF (34 percent soil moisture) than any other treatment (fig 4). F and CF were not significantly different (28 percent), and all treatments including either mounding or bedding lowered moisture levels to around 20 percent. In 2005 ($p < 0.0001$), soil moisture on the three flat planted treatments was not significantly different and averaged 32 percent. Of the remaining treatments, soil moisture was lowest on HM (17 percent), although moisture levels only ranged from 17 to 22 percent for treatments including mounding or bedding.

DISCUSSION

The site preparation treatments used in this study did not significantly affect survival rates during the first two growing seasons following treatment application. In a study on well-drained sites of FL, bedding reduced survival of planted longleaf pine seedlings by 11 percent when compared to a shear and rake treatment (Loveless and others 1989). Additionally, Boyer (1988) found that container-grown seedlings planted on sites treated with herbicides had lower survival rates (71 percent) than those receiving no treatment (87 percent) three years after planting. Early longleaf pine survival has been reported to vary by site (Boyer 1988, Rodriguez-Trejo and others 2003) and the impact of site preparation is also likely to be dependent on site conditions. However, our results suggest that container-grown seedlings planted on poorly drained coastal plain sites have fairly good survival regardless of site preparation.

All of the treatments used in our study, with the exception of chopping alone, resulted in greater root collar growth than the untreated check. In the first growing season, the differences in root collar diameter among the treatments were small; by the next year, however, the differences were quite pronounced. Grass stage emergence, a critical event in the establishment of a longleaf pine stand, typically occurs when seedling root collar diameter approaches 25 mm (Boyer 1990). Under unfavorable conditions, seedlings have

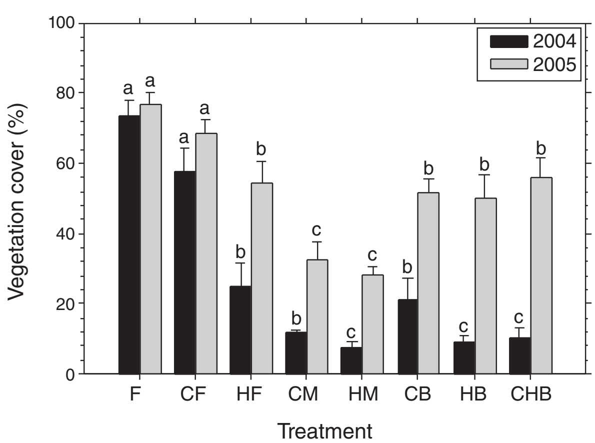

Figure 3—Percent cover of surrounding vegetation in August 2004 and August 2005 for each treatment. Similar letters within a year indicate no significant difference. Error bars are one standard error. F = flat (check), CF = chop/flat, HF = herbicide/flat, CM = chop/mound, HM = herbicide/mound, CB = chop/bed, HB = herbicide/bed, CHB = chop/herbicide/bed.

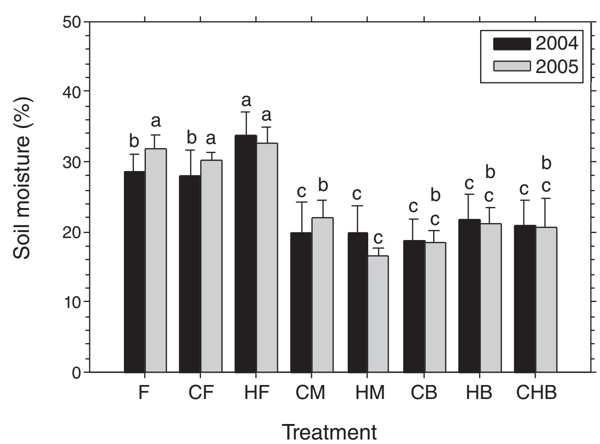

Figure 4—Percent soil moisture in 2004 and 2005 growing seasons for each treatment. Similar letters within a year indicate no significant difference. Error bars are one standard error. F = flat (check), CF = chop/flat, HF = herbicide/flat, CM = chop/mound, HM = herbicide/mound, CB = chop/bed, HB = herbicide/bed, CHB = chop/herbicide/bed.

the potential to remain in the grass stage for up to 10 years (Pessin 1944). In 2005, seedlings on F and CF averaged 14.8 mm while those on HM, HB, and CHB averaged 20.8 mm. We can expect seedlings on HM, HB, and CHB to emerge from the grass stage much earlier than those on CF and F, potentially resulting in long-term differences in stand production.

Our results are consistent with previous work suggesting that excess soil moisture on wet sites limits pine seedling growth. Flat planted sites had both the smallest seedlings and highest soil moisture contents, and treatments that reduced soil moisture coincided with large seedlings. Mounding was developed in wetlands of northern latitudes with a primary purpose of improving the drainage of planting sites (Londo and Mroz 2001, Sutton 1993) and has been shown to increase early growth of planted slash pine when applied in LA (Haywood 1987). Similarly, bedding is commonly used in the southeastern Unites States on poorly drained sites where moisture levels limit seedling growth (Miwa and others 2004). Treatments in our study that included either mounding or bedding reduced soil moisture by around 10 percent compared to those that were flat planted. Consequently, all treatments including mounding or bedding increased mean seedling growth over the check.

In our study, all treatments were expected to provide some degree of vegetation control; however, the abundance of surrounding vegetation was not significantly different between the chop-only treatment (CF) and the check in either growing season. Chopping, a site preparation designed to reduce competition by crushing standing vegetation, was apparently ineffective in decreasing abundance of surrounding vegetation. However, mechanical treatments often alter the structure and composition of ground layer vegetation (Conde and others 1983, Swindel and others 1986), and although chopping did not decrease percent cover of vegetation it may have changed the composition.

The effectiveness of vegetation control in this study appeared to change over time. In the first year, treatments that included herbicides and mechanical control had the lowest vegetation abundance; the next year, mounding treatments had significantly less vegetation cover than any other treatment. Mounding inhibits growth of vegetation by inverting the soil and providing a “cap” of mineral soil at the surface that creates a barrier to returning vegetation (Sutton 1993). Herbicides are often quite effective in the first year following application, but may not provide long term competition control without reapplication (Zutter and Zedaker 1987). As these stands continue to develop and surrounding vegetation returns, treatments that provide lasting competition control may become more important for seedling growth.

CONCLUSION

Artificial regeneration of southern pine species often includes the use of site preparation treatments that change growing conditions and increase seedling survival and growth. We found that increased growth of longleaf pine, like other southern pines planted on poorly drained sites, coincided with site preparations that improved soil drainage and reduced competing vegetation. Treatments resulting in the greatest seedling growth in this study included either bedding or mounding combined with herbicides. We found these treatments to be effective for rapidly increasing seedling growth, but recognize that they likely have other effects on the ecosystem. The objectives of the land manager will dictate whether these treatments are appropriate, and future research will help determine the effects of site preparation on other aspects of the ecosystem.

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COMPOSITION AND STRUCTURE OF MANAGED PINE STANDS COMPARED TO REFERENCE LONGLEAF PINE SITES ON MARINE CORPS BASE CAMP LEJEUNE, NORTH CAROLINA

Joan L. Walker, Andrea M. Silletti, Susan Cohen[1]

Abstract—We sampled the ground layer of 28 pine plantations to compare with ecological reference sites at Marine Corps Base, Camp Lejeune (MCBCL), NC. Plantations were ≥ 18 years old and had been burned within the previous year. Pines had been hand-planted on beds or flat-planted, and the plantations were burned every 3 to 4 years after age 7. Data from 39 reference sites were acquired from the Carolina Vegetation Survey database, and included MCBCL sites that had been maintained by regular burning. We used non-metric dimensional scaling to detect patterns in the data. Ordination arrayed plots by canopy structure and soil base saturation on one axis and by diversity measures on a second. Results of a multi-response permutation procedure indicated that the compositional difference between the groups was significant ($p<.0001$). Although species richness in plantations was consistently lower than that in reference sites, the differences were significant ($p<.05$) only at small scales. Results confirmed a reduction in desirable native ground layer species along with increased shrub cover and woody stem density, in spite of regular prescribed burning.

INTRODUCTION

The current Southeastern landscape has hundreds of thousands of hectares in pine plantations on sites once dominated by longleaf pine, and it is clear that plantation establishment and management will continue to be effective systems for increasing pine habitat. While there is considerable information available about the effects of plantation establishment, especially of site preparation methods, on ground layer vegetation, the longer-term effects of plantation establishment on ground layer vegetation are not well-documented. Walker and van Eerden (1996) and Smith and others (2002) reported reduced species richness at small scales in plantations (30 to 40 years old) compared to reference sites in the fall line sandhills. Species richness in xeric site plantations nearly equaled reference sites at a scale of 0.1 ha; however, several key ground cover species were significantly ($p<.05$) reduced. The cover of the dominant bunch grass, *Aristida stricta*, and the dominant dwarf shrub, *Gaylussacia dumosa*, were reduced in xeric longleaf pine plantations in Chesterfield County, SC (Walker and van Eerden 1996). Smith and others (2002) reported a similar pattern in stands sampled across a moisture gradient from xeric to sub-mesic sites at the Savannah River Site, SC; however, there is no information available to examine this hypothesis on mesic to wet-mesic sites. Understanding this relationship is important if we are to develop site-specific restoration protocols.

This study was undertaken to investigate the potential persistent or cumulative effects of pine plantation establishment and growth on ground-layer vegetation in sites that range from well-drained to somewhat poorly drained, and which were historically occupied by longleaf pine communities. We approached the problem by comparing established plantations with reference longleaf pine communities on similar site types. This report includes the preliminary analysis of these data; results of additional analyses will be reported elsewhere.

METHODS

Study Area

Marine Corps Base Camp Lejeune (MCBCL) near Jacksonville, NC, occupies 50 585 ha (125 000 acres) in the Atlantic Coastal Flatlands Section of the Outer Coastal Plains Mixed Forest Province (Bailey 1995, USMC 2001). The Atlantic Ocean forms its eastern border, and the New River inlet is a dominant feature in the center of the base. Camp Lejeune has both well-draining, gently rolling terrain and poorly draining broad, level flatlands. East of the New River, the flatlands range in elevation from 7.6 to 13.7 m; between New River and US Hwy 17, the changes in elevation are more pronounced—as high as 22.0 m, and west of US 17, elevation ranges from 11.9 to 21.0 m.

The natural longleaf vegetation type was wet, mesic, or xeric longleaf or mixed pine savannas (Frost 2001). The typical stands had an open canopy of longleaf or mixed pines (pond pine on wet sites) and a low ground layer that ranged from graminoid dominance with a high diversity of forbs to dwarf shrub dominance with a mixture of graminoids and forbs. The characteristic structure was maintained by a frequent, low-intensity, surface fire regime. The historical fire-return interval is estimated to be one to three years.

Recent management included prescribed burning with a return interval of about three years, although active weapon-firing ranges might burn annually. Through the 1970s and 1980s the natural resources staff managed pine stands to maintain production using even-aged systems typical of the general forest management practices of the time. Currently, pine stands are regenerated primarily to restore longleaf pine for red-cockaded woodpecker habitat, but existing plantations are managed to maintain their vigor and economic value. Most of the stands sampled in this study were artificially regenerated, but the intensity of site preparation varied.

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Site Selection

Plantations were sampled during the summers of 2003 and 2004. Sites were located on the following soil series: Kureb fine sand, Baymeade fine sand, Leon fine sand, Murville fine sand, Norfolk loamy fine sand, Onslow loamy fine sand, Stallings loamy fine sand, Wando fine sand, and Woodington loamy fine sand. We sampled sites at least 18 years old so that we could capture stands where intensive site preparation methods had been applied; the base began using a bedding plow for site preparation in 1986. By age 18, the canopy had closed and some stands had received a first thinning, usually a row thinning that removed every third row. Vegetation changes rapidly following fire; in order to minimize the effects of this change, we restricted site selection to areas that had been burned within 12 months prior to sampling. We included 28 stands in this analysis.

We acquired ecological reference plot data from the Carolina Vegetation Survey (CVS) plot database archived by the Herbarium at the University of North Carolina, Chapel Hill, NC. Data collection standards are described at http://www.bio.unc.edu/faculty/peet/lab/CVS/ (Site referenced June 1, 2007). From all plot data collected within the boundaries of Camp Lejeune, we selected 39 plots dominated by longleaf pine, or a mixture of longleaf with loblolly or pond pines. All soil series in reference plots were represented among plantations except Foreston loamy fine sand and Alpin fine sand.

Data Collection and Manipulation

Plots were sampled using the CVS protocol described by Peet and others (1998). This protocol is based on a 10 m by 10 m module, with an array of 10 modules representing a complete plot sample (0.1 ha). Within each of up to four intensively sampled modules, species presence was recorded in two sets of nested subplots sized 0.01 to 10 m^2. Within each plot, rooted vascular plant species richness (S) was estimated for six nested areas regularly spaced on a log-10 scale, from 0.01 to 1 000 m^2. Richness values for areas less than 0.1 ha were averaged to estimate richness at the plot level. Species cover was estimated at the module level using cover classes: 10 = 95 to100 percent, 9 = 75 to 95, 8 = 50 to 75, 6 = 10 to 25, 5 = 5 to 10, 4 = 2 to 5, 3 = 1 to 2, 2 = <1 to 1 = trace. For analyses, cover class values were converted to the mid-points of cover classes, averaged for the plot, and re-converted to cover classes for analyses. Mean plot abundance and richness at the plot level were used to calculate the Shannon-Weiner diversity index (H') and Simpson's diversity index (D). In each plot, trees greater than 2.5 cm d.b.h. were tallied by size class and species. We calculated density and basal area for all woody stems combined, for all pines, and for all hardwoods.

Five soil samples were collected from the top 10 cm of each plot, and pooled for analyses. Soils from managed pine stands were analyzed in the Forestry Sciences Lab, RTP, NC. Soils from CVS reference sites were analyzed by Brookside Labs, Knoxville, OH. The following soil variables were evaluated for correlations with ordination axes: cation exchange capacity (CEC), percent base saturation by K^+ (K_{sat}), Mg+2 (Mg_{sat}), and Ca^{+2} (Ca_{sat}); pH; organic matter (OM); extractable K^+, Mg^{+2}, Ca^{+2}; percent sand, silt, and clay.

Vascular plant taxonomic concepts and nomenclature were standardized to follow Kartesz (1999). In order to minimize the effects of possible plant identification inconsistencies among field crews, especially of difficult plant groups (e.g. vegetative *Dichanthelium* spp.), we combined taxa except those we judged to be easily identified correctly by most field botanists, and we did not recognize subspecific taxa.

Data Analysis

We used non-metric multidimensional scaling (NMS) ordination to represent the variation in ground layer communities in plantations and reference sites (Clarke 1993, Minchin 1997). Ordinations were performed with the number of dimensions ranging from 1 through 6, and to avoid local minima 40 different random starting configurations were used. A Monte Carlo test based on 50 randomizations of the vegetation data matrix was used to determine the probability that a similar final stress could have been obtained by chance. We ran the procedure for 400 iterations to get the final solution with real data. We examined the scree plot (line graph of minimum stress versus number of dimensions) to identify the number of dimensions beyond which further reductions in stress were relatively minor (Kruskal 1964).

We tested for community differences between plantations and reference sites using a multi-response permutation procedure (MRPP) (Biondini and others 1985, Mielke and Berry 2001). MRPP is a non-parametric procedure for testing the hypothesis of no difference between two or more groups of entities, in this case between entries in a distance matrix. The chance-corrected within-group agreement, A, describes within-group homogeneity compared to the random expectation. When all items are identical within groups, A = 1; if heterogeneity within groups equals expectation by chance, then A = 0; if there is less agreement within groups than expected by chance, then A<0. A>0.3 is high for ecological data (McCune and Grace 2002). NMS and MRPP were performed using PC-ORD version 4 (McCune and Mefford 1999).

We used analysis of variance procedures to test for a site type (reference versus managed pine) effect on density and basal area of all woody species, of pines, and of hardwoods; on species richness at various spatial scales; and on cover of selected species and species growth form groups (woody and herbaceous species).

RESULTS

The NMS ordination resulted in three dimensions as optimal for representing the variation in the plot data. The proportions of variance in the original distance matrix that were represented by NMS axes 1, 2, and 3 were 0.426, 0.205, and 0.252, respectively. Correlations of environmental and structural data were generally low (Table 1). Because pH was the only explanatory variable associated with Axis 2 with an r^2>0.15, and Axis 2 represented the least variance in data, we show the array of plots on Axes 1 and 3 only (fig. 1). In general, position on Axis 1 was correlated positively with stand age, Mg_{sat}, and Ca_{sat}, and negatively with the basal area of pines and total basal area, and K^+. Axis 3 was related most strongly with measures of plot diversity (S, H', and D).

Table 1—Pearson and Kendall correlations of environmental and stand structural parameters with NMS ordination axes

	Axis 1			Axis 3		
	r	r-square	tau	r	r-square	tau
CEC, μeq	0.327	0.107	-0.19	0.254	0.064	0.188
Ksat, %	0.027	0.001	0.278	-0.146	0.021	-0.128
Mgsat, %	0.585	0.342	0.416	-0.289	0.083	-0.227
Casat, %	0.503	0.253	0.298	-0.253	0.064	-0.263
pH	0.375	0.141	-0.331	0.069	0.005	0.027
OM, %	0.367	0.135	-0.368	0.256	0.065	0.208
K, ppm	0.427	0.183	-0.186	0.079	0.006	0.087
Mg, ppm	0.209	0.044	0.136	0.167	0.028	0.027
Ca, ppm	0.195	0.038	0.16	0.146	0.021	-0.085
Clay, %	0.068	0.005	0.028	-0.072	0.005	0.002
Silt, %	0.201	0.041	-0.059	0.208	0.043	0.093
Sand, %	0.191	0.036	0.059	-0.197	0.039	-0.093
Total tree density, stems/ha	0.179	0.032	-0.275	-0.026	0.001	0.063
Total basal area, m^2/ha	0.425	0.181	-0.405	-0.021	0	0.033
Pine density, stems/ha	-0.26	0.067	-0.193	-0.028	0.001	0.17
Pine basal area, m^2/ha	0.426	0.181	-0.355	0.015	0	0.1
Hardwood density, stems/ha	0.002	0	-0.181	-0.036	0.001	-0.076
Hrdwd basal area, m^2/ha	0.166	0.027	-0.212	-0.22	0.048	-0.152
Richness (S), number of species	0.054	0.003	0.005	0.572	0.327	0.403
Evenness (E)[a]	0.083	0.007	-0.064	0.471	0.222	0.339
Shannon-Weiner index (H')	0.042	0.002	-0.007	0.58	0.337	0.416
Simpson's index (D)	0.052	0.003	-0.017	0.539	0.291	0.432

[a] See McCune and Grace (2002) for definitions of E, H', and D.

MRPP generated a low A (0.06), but the difference was statistically significant at p<0.0001. A low A suggests that the differences within groups were not much greater than that expected by chance alone. This may result from the high variability among the managed pine stands, making it difficult for actual data to differ from randomly generated data in the permutation procedure. The result is consistent with the separation of groups by NMS.

Site type had a significant effect (p<0.0001) on species richness at scales of 0.1 m^2, 1 m^2 and 10 m^2, such that reference sites richness exceeded richness in managed pine stands (fig. 2). At spatial scales of 100 and 1000 m^2, differences between site types were not significant.

Summaries of variables associated with NMS ordinations are shown in Table 2. Compared to reference sites, plantation soils had higher pH, higher extractable potassium, lower Ca saturation, and lower Mg saturation. We found that plantations had significantly higher total and pine basal area than reference stands. Plantations and reference sites were not different with respect to three measures of ground layer vegetation structure (S, H', D) but there was a site type effect on evenness (E).

The total ground cover in reference sites exceeded that in plantations (113 versus 81 percent; table 3). The difference was mostly in the herbaceous component which had almost twice the cover in reference sites compared to plantations (43 vs. 24 percent). *Aristida stricta*, *Gaylussacia dumosa* and *Pinus palustris* were more abundant in reference sites than in plantations by factors of 5, 10 and 6 respectively. *Gaylussacia frondosa*, which is similar to *G. dumosa* in growth form but tends to be more abundant on wetter sites than *G. dumosa*, was not different between the site types.

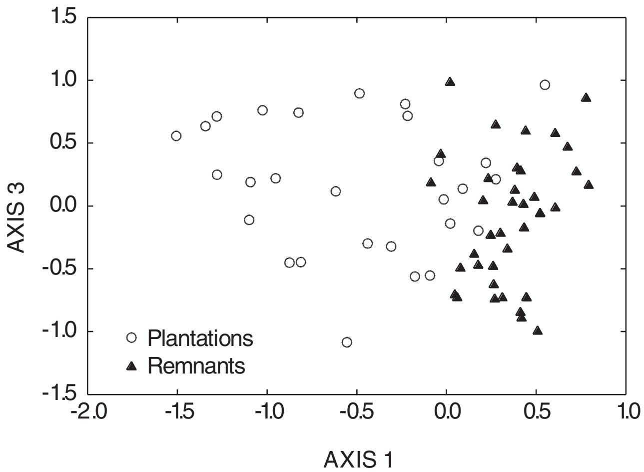

Figure 1—Non-metric multidimensional scaling (NMS) ordination of plantation and reference plots.

DISCUSSION

Overall, plantations ≥18 years old differ compositionally and structurally from ecological reference sites. The loss of potentially dominant groundcover species, such as *Aristida stricta*, *Gaylussacia dumosa*, and *Pinus palustris* seedlings, is consistent with observations in similar comparisons of plantations to reference stands in the sandhills of SC (Smith and others 2002, Walker and van Eerden 1996). In xeric sandhills plantations, species composition was similar to reference sites, except for the conspicuous losses of *A. stricta* and *G. dumosa*. As in the Camp Lejeune study, sandhills plantations had significantly higher pine densities and basal areas than comparable reference sites.

The lack of difference in species richness except at the smallest scales indicates that reasonably diverse communities are maintained in plantations, and suggests the potential for restoring a diverse groundcover without adding species. However, as noted previously, a few dominant species apparently are sensitive to habitat modifications created during establishment and growth of plantations. Although thinning the canopy and prescribed burning may invigorate the groundcover (Provencher and others 2001), we predict that the effectiveness of prescribed burning may be limited by the lack of fine fuels resulting from the significantly reduced herbaceous cover in plantations. Restoring the continuity of fine fuels is likely to require reintroducing the dominant large grasses found in reference sites.

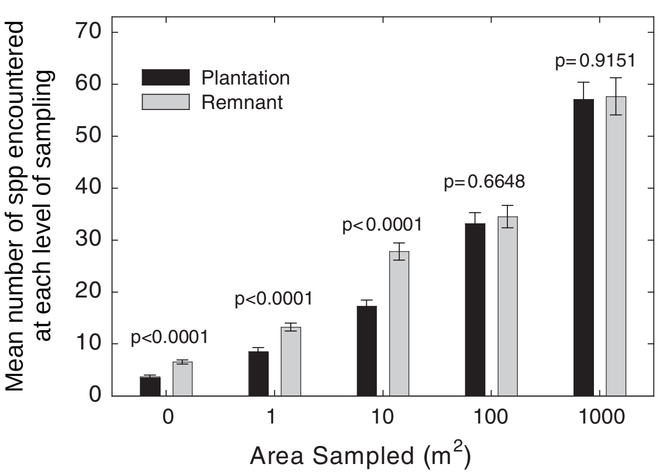

Figure 2—Species richness (number of species counted) at five different sampling scales in plantations and reference sites. Shown are means (±1SE). P-values above pairs of bars indicate result of one-way ANOVAs testing the effect of site type (plantation versus reference) on species richness at each scale.

We expected stronger relationships between ordination scores and environmental parameters; specifically, we expected stands would be ordered strongly by soil texture. The relationship of composition to soil texture, widely regarded as a surrogate for soil moisture availability, is well-established for natural stands (Christensen 1988, Peet and Allard 1993, Walker and Peet 1983). We predict that an analysis of the reference sites alone would reveal a compositional gradient that follows soil texture, but that such a relationship would not be found in an analysis of plantations. In a comparison of plantations and reference sites in the Fall-line sandhills of SC, Smith and others (2002) reported that the expected strong relationship between ground layer composition and soil texture was evident for both plantations and reference natural areas; however, the difference between plantations and reference sites was greater at the mesic end of the environmental gradient than in xeric sites. Thus, the strength of the relationship to soil texture is not simply related to the disturbance associated with plantation establishment.

We hypothesize that the degree to which plantation management disrupts natural diversity and community structure is related to both site conditions and management choices. On drier sites, less intense silviculture methods are required to establish longleaf plantations, thus the initial losses in the groundcover are less than in wet sites. In addition, re-growth of competing vegetation is slower on drier sites than on wet sites, resulting in a comparatively low loss of groundcover diversity (changing composition) in the early establishment period before prescribed fire can be introduced. Finally, in wetter sites, planted loblolly and slash pines were protected from prescribed burning for the first five to seven years, thus exacerbating the loss to aggressive shrubs and hardwoods. In summary, we hypothesize that plantations on wet sites are inherently more variable than those on drier sites, because establishment methods are more variable and early stand management varies with the species of pine planted. In the rapid and profound changes that occur on wet sites, characteristic species are lost to more widespread, weedy ones, both herbaceous and woody, thereby obscuring species habitat relationships that govern species distributions in the undisturbed landscape.

MANAGEMENT IMPLICATIONS

Compared to ecological reference sites, plantations (≥18 years old) at Camp Lejeune have a greater pine basal area (and total basal area) and reduced cover of the characteristic dominant grass (wiregrass). These results suggest that in

Table 2—Mean (standard error) of soil characteristics and structural variables correlated with NMS axes (r-square ≥ 0.15), by site type

	Reference (n=28)	Plantation (n=39)	F[a]	p[a]
pH	3.95(0.05)	4.18(0.05)	8.83	0.0042
K (mg/kg or ppm)	21.79(1.86)	38.10(3.56)	19.10	<0.0001
Ca saturation (%)	17.40(0.86)	5.50(0.79)	94.97	<0.0001
Mg saturation (%)	6.34(0.19)	2.32(0.34)	118.10	<0.0001
Total tree basal area (m^2/ha)	11.34(0.72)	23.07(4.31)	9.84	0.003
Pine basal area (m^2/ha)	9.98(0.75)	21.17(3.98)	10.36	0.002
Species richness (S)	54.51(2.90)	53.18(3.01)	0.10	0.756
Species diversity (H')	3.81(0.06)	3.82(0.07)	0.01	0.929
Species diversity (D)	0.97(0.002)	0.97(0.002)	0.01	0.905
Evenness (E)	0.96(0.002)	0.97(0.002)	4.30	0.042

[a]F and p are the test statistic and significance level, respectively, from the associated ANOVA for site type effect.

Table 3—Mean (standard error) percent cover in the ground layer vegetation (< 1 m tall) of (a) herbaceous, woody and all species and (b) selected species in plantations and reference forests

	Plantations (n=28)	References (n=39)	F[a]	p[a]
(a) Growth form group				
Herbaceous species	23.79(2.79)	43.20(4.48)	11.17	0.0014
Woody species	56.98(6.31)	70.04(6.05)	2.14	0.1480
Total cover	80.77(7.37)	113.24(6.12)	11.54	0.0012
(b) Selected species				
Aristida stricta	4.02(1.54)	21.83(3.82)	14.36	0.0003
Gaylussacia dumosa	0.51(0.11)	9.06(1.98)	13.36	0.0005
Gaylussacia frondosa	4.05(1.14)	7.95(1.53)	3.61	0.620
Pinus palustris	2.50(0.92)	15.28(2.59)	16.39	0.0001

[a]F and p are the test statistic and significance level, respectively, from the associated ANOVA for site type effect.

order to restore these plantations to reference conditions managers will have to both increase the bunch grass cover and thin the canopy. However, because thinning may release understory hardwoods that will compete with planted grasses, the order of treatments and subsequent competition control must be carefully considered.

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IMPACT OF HURRICANE IVAN ON THE REGIONAL LONGLEAF PINE GROWTH STUDY: IS THERE A RELATION TO SITE OR STAND CONDITIONS?

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Abstract—The US Forest Service Regional Longleaf Pine Growth Study (RLGS) began its eighth re-measurement (40th year) during 2004 autumn. The study has 305 plots of which 171 plots are located on the Escambia Experimental Forest (EEF) in Brewton AL. EEF is operated by the U.S. Forest Service in cooperation with the T.R. Miller Mill Company. The RLGS has plots distributed across a range of age, site and density (basal area) classes. On September 16, 2004 Hurricane Ivan hit the Alabama coast and severely impacted numerous RLGS plots. Nearly 1/3 of the EEF was impacted. Thirteen plots, which had pole-size trees, were entirely lost. Another 125 plots experienced some type of mortality. The greatest damage was on plots with the lowest density or located near openings. Nearly 30 percent of trees greater than 80 years old had their tops snapped off. There was little relation between these site conditions and impacts from the hurricane.

INTRODUCTION

Numerous climate models are predicting global warming which will lead to more frequent and intense hurricanes for the Southeastern United States. These scenarios have serious implications for forest management. Several research papers have discussed the impacts of hurricanes to forested stands, including a compilation about the impacts from Hurricane Hugo (Haymond and Harms 1996).

In the very early morning of September 16, 2004, Hurricane Ivan came ashore near Orange Beach, AL, southeast of Mobile, AL with winds in excess of 120 miles per hour. It maintained hurricane force winds for the next several hours as it traveled through west-central Alabama. At 4:00 a.m. on the morning of the 16th, the eye wall of the hurricane was approximately 15 miles to the west of Brewton, AL, location of the Escambia Experimental Forest (EEF). Winds at a National Weather Service station located in Brewton had measured wind speeds of 120 miles per hour as the hurricane and associated winds passed through.

The EEF has been conducting longleaf pine (*Pinus palustris* Mill.) research since 1947 (Boyer and others 1997). It is operated by the US Forest Service in cooperation with the T.R. Miller Mill Company in Brewton, AL. The EEF contains nearly 60 percent of the Regional Longleaf Pine Growth Study (RLGS) plots. From 1964 to 1967, Dr. Robert M. Farrar Jr., with the U.S. Forest Service, established the RLGS in the Gulf States (Farrar 1978). The original objective of the study was to obtain a database for the development of growth and yield predictions for naturally regenerated, even-aged longleaf pine stands. The RLGS consists of 292 1/5-acre and 13 1/10-acre permanent measurement plots located in central and southern AL, southern MS, southwest GA, northern FL, and the sandhills of NC. The plots are inventoried on a 5-year cycle and are thinned at each inventory, as needed, to maintain the assigned density level. Plots cover a range of age classes from 20 to 120 years, five site-index classes, ranging from 40 to 80 feet at 50 years, and five density classes, ranging from 30 to 150 square feet per acre, with a new class recently added of “free to grow” to see what is the maximum density longleaf pine stands can attain prior to extensive mortality setting in. Densities are established and maintained by low thinning. The study accounts for growth change over time by adding a new set of plots in the youngest age class every 10 years. Within this distribution are five time replications of the youngest age class. All five replications are located on the EEF. The project will complete its eighth re-measurement (40-year measurement) in spring 2007 (Kush and others 1987, 1998).

Work had begun on the eighth re-measurement of the RLGS when Hurricane Ivan struck. Nearly 60 percent (171 plots) of these plots are located on the EEF. Damage to the forest was extensive and within days T.R. Miller Mill Company began to salvage snapped, downed, and leaning trees. In the midst of the salvage operation, a visit was made to each RLGS plot to record the fate of each tree. These data will be summarized based on stand and site conditions.

METHODS

Notes were made for each tree on every RLGS plot. The tree was noted as alive or dead, if dead, was it due to being snapped off or was it tipped up. If it was snapped off, the height of breakage was estimated. If the tree was alive, notes were made to whether there was no apparent damage or if it was leaning or if it had a broken top. In addition, the trees were separated out by those that were of merchantable size, diameter at breast height (d.b.h.) greater than 7.0 inches, because these trees were the focus of the salvage operation.

The tree mortality and damage data were examined based on stand conditions. The RLGS plots on the EEF cover a range of six 20-year age classes from 20 to 120 years, three 10-foot site-index classes, ranging from 60 to 80 feet at 50 years, and five 30-square feet per acre density classes, ranging from 30 to 150 square feet per acre. In addition, soil type, plot aspect and percent slope were used to examine these data. Excellent information is available about the soils because the EEF was extensively mapped in the 1970s to aid Forest Service research. The RLGS plots are found on 10 different soil series.

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The predominant soil series are Troup (41percent), Benndale (19 percent), Wagram (13 percent), and Esto (12 percent).

RESULTS AND DISCUSSION

Stand Conditions

Merchantable trees—It is estimated nearly 1/3 of the EEF was severely impacted by Hurricane Ivan. Thirteen RLGS plots were destroyed and 125 plots (73 percent) experienced some form of mortality. Only 26 (15 percent) plots had no visible impact. The thirteen destroyed plots contained all merchantable trees. In addition, 16 plots lost more than 50 percent of their basal area on plots with only merchantable trees. Only 15 plots of the 92 plots with merchantable trees had no visible impact.

Table 1 presents data collected on the RLGS trees impacted by Hurricane Ivan. The major cause of mortality among merchantable trees was caused by the top snapping off. The cause of mortality among merchantable trees was snapping off (9 percent) and another 4 percent were tipped up (blowdowns). Among the trees which snapped off, nearly 90 percent of the breakage occurred between 15-20 feet above the ground and not at the crown like might be thought.

The greatest loss of merchantable trees occurred on plots with the lowest basal areas (table 2). The more open plots and heavier crowns may have been the reason for the higher incidence of snapping off on the 30, 60 and 90 square feet per acre plots compared to the 120 and 150 square feet per acre plots. As could be expected, the highest rate of tip-ups occurred on the lowest basal area plots and decreased with increasing density. The higher rate of broken tops on the 150 square feet per acre plots may have been due to the crowns of trees hitting each other.

More than 1/4 of all merchantable trees 80 years and older were snapped off on the RLGS plots as a result of Hurricane Ivan (table 3). The obvious explanation is these are the larger trees and in more open conditions making them the most vulnerable to the winds. Very little mortality occurred to those trees 40-years-old and younger.

There were no apparent relations between site index and impacts from the hurricane (table 4). Nearly 70 percent of the RLGS plots on the EEF occur on plots with an average site index in the 70-foot class. All plots over 80 years old are site index 70 which explains the higher rates of snapping on those plots compared to the site index 60 and 80 plots.

Non-merchantable trees—Very little damage occurred to the non-merchantable trees, those trees less than 7.0 inches d.b.h. On the youngest plots, age class 20, there is very little mortality. Broken tops were the major problem as nearly five percent of these trees experienced broken tops. The most impact came from trees that are now leaning and their fate is unknown. Over two percent of the trees in the 20-year age class are leaning, but on a few plots, more than 20 percent of the trees experienced severe enough lean that they probably

Table 1—Percent of all trees and merchantable (d.b.h. > 7.0 inches) trees sampled by the RLGS on the EEF impacted by Hurricane Ivan

Tree class	Snapped	Tip-up	Broken Top	Leaning
	percent			
All Trees	4.3	1.1	4.9	2.2
Merchantable trees	8.9	3.9	5.4	1.7

Table 2—Percent of RLGS merchantable trees on the EEF impacted by Hurricane Ivan by basal area class

Basal area class	Snapped	Tip-up	Broken top	Leaning
(square feet/acre)	*percent*			
30	12.9	7.2	0.0	3.2
60	11.9	5.4	0.8	0.6
90	14.3	5.2	4.7	1.2
120	5.9	3.2	4.7	2.1
150	6.2	1.7	13.9	1.7

Table 3—Percent of RLGS merchantable trees on the EEF impacted by Hurricane Ivan by age class

Age class	Snapped	Tip-up	Broken Top	Leaning
(years)	*percent*			
40	0.8	0.0	6.3	0.5
60	7.6	4.8	6.1	2.8
80	29.9	7.3	8.8	1.5
100	25.6	10.4	1.8	2.1

Table 4—Percent of RLGS merchantable trees on the EEF impacted by Hurricane Ivan by site index class

Site index class	Snapped	Tip-up	Broken top	Leaning
(feet at base-age 50)	*percent*			
60	8.3	2.5	7.4	0.0
70	13.6	4.4	5.4	1.1
80	6.4	3.7	5.2	2.1

will not recover. In all cases, the trees were leaning in a southeast-to-northwest direction.

Site Conditions

Percent slope was not a factor in the impacts from Hurricane Ivan to the EEF RLGS plots. Most of the EEF is relatively flat with slopes of zero to three percent for most of the forest. There appears to be a role with aspect as 7 of the 13 plots destroyed had an aspect classified as south-to-west. In addition, plots with a southwesterly aspect accounted for 20 percent of trees lost.

Among the major soil series, every plot on the Esto series experienced some type of mortality and 18 percent of the plots lost more than 50 percent of their basal area. The Esto soil series have the shallowest soils of the major soils series on the EEF. The Benndale and Wagram soil series were similar in the impacts from Hurricane Ivan. Nearly 94 percent of the plots experienced some type of mortality and approximately one-third of the plots lost more than 50 percent of their basal area. The Troup soil series, with the deepest A-horizon, experienced the least amount of loss. Only 50 percent of the plots had mortality with only 8 percent of the plots losing more than 50 percent of their basal area.

CONCLUSIONS

Hurricanes are chaotic events! There are no definitive findings about the impacts of Hurricane Ivan to the RLGS plots located on the EEF. It can be noted that 11 of the 13 plots destroyed were open to their east side. Nine of these 13 plots were adjacent to a woods road. These two findings indicated the plots more protected with other trees around them did better than those in an opening or with a lower basal area. The major management implication is to keep a higher density out there to protect stands. Unless there is longleaf regeneration on the ground, once the overstory is lost, there is no hope of returning the site in longleaf unless the trees are planted.

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INITIAL EFFECTS FROM RE-INTRODUCING FIRE IN ALABAMA MONTANE LONGLEAF STANDS: FIFTY YEARS SINCE LAST BURN

Sharon M. Hermann and John S. Kush[1]

Abstract—In 2006, after more than fifty years with no burns, the National Park Service reintroduced fire in montane longleaf pine stands at Horseshoe Bend National Military Park in central AL. Residual longleaf pine stands indicates that this tree once dominated many slopes. The prolonged period of fire exclusion resulted in accumulation of duff and litter that exceeds 4 to 5 inches in places; especially heavy loads were found at bases of residual longleaf pine (50-80 year old). In an effort to minimize injury to adult longleaf from smoldering fire, heading and flanking ignition patterns were recommended. In addition, selected tree bases were soaked with approximately 50 gallon of water a day prior to the burn. Preliminary evaluation indicates that this treatment was effective but costly. Recent observations suggest that, even under moderate weather conditions and moist duff, backing fires have high potential for smoldering near large trees.

INTRODUCTION

It is widely accepted that the current acreage of longleaf pine (*Pinus palustris* Mill.) forest represents a small percentage (about 3 percent) of its extent 200 years ago (Frost 1993). Although there is increasing awareness of the importance of frequent fire to this ecosystem, a recent review by Outcalt (2000) revealed that almost 50 percent of existing longleaf stands had not been burned in the previous five years. When fire is excluded many changes occur. Factors that are expected to increase are litter depth and number of woody stems, especially of hardwoods and non-longleaf pines. In addition, longleaf recruitment is likely to decrease and, if fire is excluded long enough, duff may form. The more years that fire is excluded from a site, the greater the challenge will be to reintroduce it and restore the stand.

For efforts to reintroduce fire to be worthwhile, they must be offset by expected enhanced economic and/or ecological value of the restored stand. To make this assessment, it is necessary to compare current degraded stand conditions to a reference site. There is a basic understanding of desired conditions for longleaf ecosystems in the coastal plain, based on existing old-growth stands (cf. Platt and others 1988) coupled with descriptions from the eighteenth and nineteenth centuries (Bartram 1791, Sargent 1884, Mohr 1896). Old-growth characteristics of montane longleaf forest, north of the Fall Line, are less well known (but see Varner and others 2003).

In this paper, we describe upland stands in Horseshoe Bend National Military Park (HOBE), owned and managed by the National Park Service (NPS) in Tallapoosa County in central AL. NPS records indicate that fire has been excluded from the 2,100 acre site for more than 50 years and regional accounts suggest that the area was logged in the early 1900s. We summarize early descriptions of nearby uplands and make comparisons between 100 year old timber cruise information provided by Reed (1905) from Coosa County, approximately 50 miles west of Tallapoosa County, and the modern upland landscape of HOBE to provide an estimation of degradation of the ecosystem. In addition we present information on the 2005–2006 fuel load, describe the first reintroduction of fire, evaluate pre- and post-burn levels of fine fuel (litter and duff), and suggest future activities to reclaim and enhance longleaf pine stands at HOBE.

EARLY DESCRIPTIONS OF REGIONAL UPLANDS

There are many fewer descriptions of longleaf forest above the Fall Line compared to Coastal Plain regions. There are two general descriptions that are relevant to HOBE. In 1775, Bartram viewed a “vast open forest” with longleaf, loblolly (*Pinus taeda*) and hardwoods on hills approximately 40 miles south of HOBE (Bartram 1791). In 1814, at the beginning of the battle of Horseshoe Bend in the Creek Indian War, Brig. General John Coffee wrote a letter to Major General Andrew Jackson to report that he had established a battle line “in an open hilly woodland” (Coffee 1814). Although neither narrative is explicit, both indicated the presence of open canopied forest; in addition Bartram (1791) confirmed that longleaf pine grew nearby.

Reed (1905) provided detailed information for a large forested area in Coosa County, AL, approximately 50 miles west of HOBE. Although this work was done a century after the earlier reports, large-scale logging and fire suppression were only beginning in the region. Reed (1905) provided a photograph of a recently burned longleaf stand. He noted that longleaf pine was present in a variety of upland areas and dominated the forest on ridges plus on south and west facing slopes.

METHODS

Forest Inventories 2005 and 2006

We extracted data from tables provided by Reed (1905) and pooled timber information for west and south facing upland slopes. Unfortunately the data in Reed (1905) does not permit estimation of variation.

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In 2005, all upland areas of HOBE were systematically searched for large longleaf pine trees by selecting a compass bearing and walking lines. The three densest stands of longleaf pine were identified and 100 percent cruises were done in each stand of 5 to 6 acres. All longleaf encountered were stem mapped and diameter at breast height (d.b.h.) measured, regardless of size. In addition, in each of the three longleaf stands, all non-longleaf pines and hardwood stems ≥ 4 inches d.b.h. were identified, stem mapped and d.b.h. measured. Information on number of hardwood stems is summarized in Hermann and Kush (2006).

Evaluation of Fuel after 50+ Years of Fire Exclusion

At HOBE, categories of fuel monitored were litter, duff, 10 hour, 100 hour, and 1000 hour fuels. The Fire Monitoring Handbook (FMH) (USDI National Park Service 2003) provides definitions of fuel categories. Fuel is any organic matter (living or dead) that will burn. Litter is dead leaves, needles, pine cones, etc. that remain identifiable. Duff is decomposed vegetation that includes fermentation and humus layers. Larger woody debris is divided into categories based on the estimated time lag for fuel to gain or lose moisture with changes in the environment. Larger diameter stems are associated with longer time lags. Fuel was assessed at different micro-sites and scales.

In order to gain experience in burning fire-excluded areas before tackling units with the highest ecological value, none of the dense stands of longleaf were burned in 2006. However, in the three stands with dense longleaf, litter and duff were assessed near the base of large longleaf trees and in gaps away from large longleaf. In each stand, four gap areas were selected based on maps created from the GIS data. In each of the four gaps, three, 130-feet long transects were spaced with at least 50 feet between transects. Every 18 feet, depths of litter and duff were measured to the nearest half-inch for a total of 96 sample points per stand.

To initiate fire effects monitoring, a standard 66 by 164 feet FMH plot was installed in a 2 to 3 acres stand of sparse longleaf pine embedded in a compartment burned in 2006. Pre- and post-burn information was collected on litter, duff, and woody debris. Details of the FMH plot methods are described by USDI National Park Service (2003).

Prescribed Fire Weather, Ignition, and Behavior

On April 6, 2006, the first burns in more than 50 years were conducted at HOBE. Information on weather, ignition pattern, and fire behavior were recorded by NPS staff using methods described in USDI National Park Service (2003).

RESULTS AND DISCUSSION

Forest Inventories 1905 and 2005

Information presented in Reed (1905) indicates that on south and west facing slopes adult longleaf ≥ 6 inches d.b.h. were common in Coosa County AL in 1905 (table 1). Non-longleaf pines (loblolly and/or shortleaf) were present but accounted for only 16 percent of the trees. In addition, Reed (1905) noted that there were sparse, scattered hardwoods in Coosa County uplands. However the low density of these trees created little or economic value and they were not included in cruise data. Data collected a century later in the three extant stands at HOBE reveals relatively similar densities of adult longleaf compared to the 1905 forest. There appears to be an increase in the density of non-longleaf pines, and there has certainly been a substantial increase in density of hardwood stems compared to one hundred years earlier (table 1). Changes in forest composition at HOBE are related, in large part, to the lack of fire in over fifty years coupled with past logging activities.

Table 1—Tree composition for stems ≥ 6 inches DBH from Reed (1905) for south and west facing slopes in Coosa County and tallied for three residual longleaf stands at HOBE in 2005. According to Reed (1905), hardwoods were present in 1905 but were uncommon on south and west facing slopes in Coosa County, AL

	Estimated number of trees per acre			
Tree type	Coosa Co 1905	HOBE NE 2005	HOBE NW 2005	HOBE SW 2005
Longleaf pine	42	37	27	32
Other pines	8	20	21	30
Hardwoods	uncommon	44	40	39

While density of adult longleaf is relatively similar between Coosa County in 1905 and at HOBE in 2005, the same is not true for juveniles. In 1905 on south and west facing slopes, the size class distribution of longleaf stems depicts a reverse J-shape curve with a relatively large number of small trees (table 2). This is similar to the size-class population structure associated with old-growth conditions for this forest type in the Coastal Plain (Platt and others 1988). This is in contrast to the three 2005 HOBE longleaf stands that supported almost no longleaf < 5 inches d.b.h. (table 2). Almost complete absence of juvenile longleaf at HOBE reflects the lack of fire. Longleaf seedlings need bare mineral soil for successful establishment and HOBE had little exposed substrate for 50+ years. For longleaf pine stands to support a range of size- (age-) classes, fire frequencies of three to five times a decade are required. Because HOBE has missed > 15 burns, longleaf recruitment has been absent.

Although HOBE lacks younger size-classes of longleaf pine, density of adult longleaf in the three surveyed dense stands mirrors the density observed in natural stands of a century earlier. These residual adult longleaf are valuable resources for future forest restoration efforts at HOBE. The existence of cone-producing sized trees could result in natural regeneration decades ahead of a project relying on planting seedlings in the near future. Although invasion of hardwoods into longleaf stands will require aggressive management to reverse, the presence of residual adult longleaf may offset the effort required to reduce the hardwoods.

Fuel Loads

Litter and duff were measured in the dense stands of longleaf because these sites have high ecological value and it is important to know about the level of fuel accumulation prior to reintroduction of fire. Across the stands of dense longleaf,

Table 2—Estimated number of longleaf trees per acre by d.b.h. category summarized from Reed (1905) for south and west facing slopes in Coosa County and tallied for three residual longleaf stands at HOBE in 2005

d.b.h. (inches)	Estimated number of longleaf pine trees per acre			
	Coosa Co 1905	HOBE NE 2005	HOBE NW 2005	HOBE SW 2005
0.1 – 4.9	20	1	0	2
5.0 – 7.9	13	7	5	7
8.0 – 10.9	9	6	10	12
11.0 – 13.9	7	11	11	14
14.0 – 16.9	6	19	7	13
17.0 – 19.9	3	9	4	3
20.0 – 22.9	3	2	0	0
23.0 – 25.9	2	0	0	0
26.0 – 28.9	1	0	0	0
29.0 +	0	0	0	0

depths of litter and duff were similar (table 3). There is no comparable data for Coosa County in 1905 but in frequently burned longleaf stands litter is expected to vary but rarely exceeds the level observed at HOBE. This suggests that current litter depth at HOBE is high but should be able to be burned. On the other hand, duff is rare in frequently burned stands and smoldering in this layer is a threat to adult longleaf (cf. Varner and others 2005). The NPS fire effects monitoring plot was located in longleaf pine but the stand was less dense and this may be reflected in the amount of litter and duff recorded in 2005 prior to burning in 2006 (table 3).

Table 3—Depth of litter and duff for 12 transects in each of three HOBE stands in 2005; each transects had 24 sample points for a total of 96 samples per stand. Transects were in areas away from the crowns of large longleaf trees. Data is also presented for a HOBE FMH plot. All data was collected in 2005; fire had been excluded from all areas for more than fifty years

	HOBE NE	HOBE NW	HOBE SW	HOBE FMH
Average litter depth (inches)	2.3	2.4	2.4	2.2
Average duff depth (inches)	2.6	2.4	2.3	0.8

Table 4 – Fuel estimated in tons per acre based on measurements provided by L. McInnis in the HOBE FMH plot

Fuel category (estimated tons per acre)	FMH 2005 (pre-burn)	FMH 2006 (post-burn)
Litter	10.90	3.62
Duff	13.00	9.50
1 hour	0.01	0.005
10 hour	0.14	0.09
100 hour	0.22	0.29
1000 hour	3.36	3.57

Prescribed Fire Preparation, Weather, Ignition, and Behavior

Fire was first reintroduced at HOBE on April 6, 2006. It must be noted that is later than recommended for re-introducing fire at sites with excessive fuels. The preferred dates would span mid-December through mid-February. However, careful planning and execution by NPS fire crews produced desirable results for the first burn. As a precaution, on April 5, crews used hose-lay to soak the bases of approximately 40 large (≥ 15 inches d.b.h.) longleaf trees. Approximately 50 gallons of water was applied to each tree that could be reached with a hose.

Day of burn weather conditions were: temperature 65-80 °F, RH 25 to 56 percent, wind 0 to 2 miles per hour with gusts of 4 miles per hour. Backing fire was the primary ignition pattern. Weather conditions coupled with heading and flanking lines of fire produced flame lengths of 0.5 to 2.0 feet and rate of spread of 1 to 3 chains per hour (20 to 60 miles per hour). These conditions likely minimized residence time near large trees and created low fire severity.

Effects of 2006 Burn

Visual post-burn assessment suggested that much of the litter but little of the duff was consumed in the first burn. By 2007, only the single FMH plot had been measured to evaluate fire effects on fuel load. In this plot, there was little change in woody fuels. However the depth of litter and the related estimate of fuel load was decreased (table 4). Although immediate post-burn inspection did not indicate duff consumption in the plot, post-burn measurements suggest a decrease in depth of duff. It is unclear if the depth of duff was actually lowered during the burn or if post-burn exposure and/or drying was involved in the decrease of depth.

Soaking appears to have been effective because there was no smoldering at the base of any treated tree. Although the re-census was not completed at the time of this report, there appears to have been at least some smoldering at the bases of approximately 1/4 of the un-soaked trees. Unfortunately this treatment was costly and required two pumper units and more than 32 person hours to accomplish.

CONCLUSIONS

For longleaf pine stands, maintenance of forest health often requires fire frequencies of 3 to 5 times a decade. HOBE has missed at least 15 burns. This has resulted in a large number of stems of off-site species and has prohibited longleaf regeneration. In addition, litter has accumulated and, perhaps most importantly, duff has formed. Duff at the base of the residual adult longleaf is an important concern because reintroduction of fire may result in smoldering at the base and subsequent mortality. Use of heading and flanking fire may have aided in creating relatively low burn severity. Use of a soaking treatment at the base of many adult longleaf a day prior to the burn appears to have minimized damage to the trees. Unfortunately, this treatment has been deemed too costly and is unlikely to be used at HOBE in the future. Other types of treatments are being considered and may include partial raking a few weeks to months prior to the next burn. It may be appropriate to consider goals that do not include total removal of duff around large trees but rather is focused on creating duff-free gaps suitable for natural regeneration near large trees.

General observations made in the fall of 2006 suggest that although a few hardwood stems were top-killed, many shrubs and understory trees increased their number of basal sprouts over the summer. Preliminary assessment indicates that 8 months after the fire there may be 3 to 8 times the original number of small hardwood stems. In the future, mechanical and/or chemical treatments may be needed until the hardwood sprouts are able to be controlled with fire alone.

Observations from a recently completed burn in 2007 help to emphasis the importance of using heading and flanking lines of fire. The burn was on January 30 and under moderate weather conditions (temperature 45-50 °F, RH 32 to 45 percent, minimal wind with gusts to 5 miles per hour). Cloud cover was high (60 to 100 percent) and the duff was moist. It was a challenge to get the burn to carry across the landscape and over much of the area a backing fire was used. This resulted in a patchy burn. Despite the low intensity fire, severity of the burn may prove to be greater than expected. In the vicinity of the HOBE NE stand of dense longleaf pine, the bases of at least six large trees were smoldering the day after the burn.

There is much work to be done at HOBE. The effects of missing 15 or more burns over 50+ years will not be rectified after one or two fires. This conclusion is shared by Kush and others (1998) and Varner and others (2005). It is likely that habitat restoration will require multiple burns coupled with short-term use of mechanical and/or chemical treatments to restructure the forest, remove litter, and decrease duff. Residual adult longleaf pines are a valuable resource for restoration if they can be protected from damage during the process of reintroducing fire (Kush and others 2004). If some cone bearing trees can survive until gap areas with no duff are created, then natural regeneration may be possible decades before it could be if restoration relied solely on planted trees.

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INFLUENCE OF REPEATED PRESCRIBED FIRE AND HERBICIDE APPLICATION ON THE FINE ROOT BIOMASS OF YOUNG LONGLEAF PINE

Mary Anne Sword Sayer and Eric A. Kuehler[1]

Abstract—Photosynthate from mature foliage provides the energy source necessary for longleaf pine (*Pinus palustris* Mill.) root system expansion. Crown scorch caused by repeated prescribed fire could decrease this energy and, in turn, reduce new root production. We conducted a study to assess the root biomass of restored longleaf pine saplings in response to three prescribed fires applied in spring over a six-year period. We observed less pine fine root biomass at the 20- to 30-cm soil depth in response to repeated prescribed fire. Absence of a similar effect at the 0- to 20-cm soil depth suggests root system sink strength at different soil depths could influence the recovery of root growth processes after crown scorch. Observations from this study will be used to refine the experimental methodology of future assessments of longleaf pine root system responses to repeated prescribed fire.

INTRODUCTION

The dramatic loss of longleaf pine (*Pinus palustris* P. Mill.) across southern landscapes between the late 1800s and mid 1900s was attributed to extensive logging, followed by regeneration failure and exclusion of fire as a management tool (Barnett and Dennington 1992, Boyer 1989, Outcalt 2000). Because the native plants and animals of longleaf pine ecosystems are adapted to, and may depend on frequent fire (Brockway and Lewis 1997, Haywood and others 2001, Landers and others 1995, Outcalt 2000), successful longleaf pine ecosystem restoration is dependent on prescribed fire. Recent recognition of fire as a necessary forest management tool in the South (Brockway and Lewis 1997, Brockway and Outcalt 2000, Gilliam and Platt 1999, Haywood and others 2001), and development of successful techniques to regenerate longleaf pine (Barnett and McGilvray 1997, Boyer 1989, McGuire and others 2001, Ramsey and others 2003, Rodríguez-Trejo and others 2003), have stimulated interest in restoring this species to portions of its natural range.

Root system expansion is required for acquisition of water and mineral nutrients, so that the physiological processes controlling tree growth are maintained. Most new longleaf pine root growth occurs in spring before drought-induced soil conditions limit root elongation (Sword Sayer and Haywood 2006). Current photosynthate is the primary energy source for root metabolism (Dickson 1991). Therefore, the amount and physiological activity of mature foliage in spring affect the supply of energy for longleaf pine root system expansion. If prescribed fire and its associated crown scorch reduce leaf area in spring, the amount of energy allocated for root growth may also be reduced. The occurrence and magnitude of this effect, however, depend on the extent of crown scorch and the ability of trees to reestablish leaf area. Our objective was to monitor the root biomass of longleaf pine saplings in response to three prescribed fires applied in spring over a six-year period. It is hypothesized that longleaf pine root biomass is reduced by repeated prescribed fire.

MATERIALS AND METHODS

Study location

The study is located on the Kisatchie National Forest in central LA. Two replications are at latitude 31° 6'N, longitude 92° 36'W on a Ruston fine sandy loam (fine-loamy, siliceous, semiactive, thermic Thermic Paleudults) containing some Malbis fine sandy loam (fine-loamy, siliceous, subactive, thermic Plinthic Paleudults) and Gore very fine sandy loam (fine, mixed, active, thermic Vertic Paleudualfs) (site 1). Three replications are at latitude 31° 1'N, longitude 92° 37'W on a Beauregard silt loam (fine-silty, siliceous, superactive, thermic Plinthaquic Plaeudults) and Malbis fine sandy loam complex (site 2). A mixed pine-hardwood forest originally occupied both sites. Site 1 was clearcut harvested in 1996 and roller-drum chopped and burned in August 1997. Site 2 was clearcut harvested, sheared, and windrowed in 1991 and burned in 1993 and 1996. Vegetation at both sites included *Schizachyrium*, *Panicum*, and *Dichanthelium* grass species that are native to western longleaf pine ecosystems (Peet 2006). Grass cover was less at site 2 than at site 1 due to the prevalence of herbaceous plants such as swamp sunflower (*Helianthus angustifolius* L.), and woody shrubs such as wax myrtle (*Morella cerifera* (L.) Small).

We established treatment plots (22 by 22 m; 0.048 ha) at each location and delineated blocks by soil drainage and topography. Three vegetation management treatments were established: (1) Control (C)—no management activities after planting, (2) Prescribed burning (B)—plots were burned using the strip headfire method in spring, and (3) Herbicides (H)—herbicides were applied after planting for herbaceous and arborescent plant control. Specifically, the H plots at site 1 were rotary tilled in December 1996. In May 1997 and April 1998, sethoxydim for grass control and hexazinone for herbaceous plant control, in aqueous solution, were applied in 0.9-m-wide bands centered over the rows of unshielded seedlings. The rate of sethoxydim application was 0.37 kg active ingredient (ai)/ha, and for hexazinone the rate was 1.12 kg ai/ha. At site 2, no tillage was necessary and only

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hexazinone was banded in April 1998 and 1999 because the sparse occurrence of grasses did not warrant the use of sethoxydim. In April 1998 and May 1999 at both sites, triclopyr at 0.0048 kg acid equivalent/liter was tank mixed with surfactant and water and applied as a directed foliar spray to competing arborescent vegetation. Recovering brush was cut by hand in February 2001. Container-grown longleaf pine seedlings from genetically improved Louisiana (site 1) and Mississippi (site 2) seed sources were planted at a spacing of 1.8 by 1.8 m in November 1997 and March 1997, respectively. Treatment plots contained 12 rows of 12 seedlings and measurement plots were the internal 8 rows of 8 seedlings in each treatment plot. Site 2 was prescribed burned in May 1998 and both sites were prescribed burned in June 2000, and May 2003 and 2005. One month after prescribed fires in 2003 and 2005, our visual evaluation of sapling crowns indicated that 80 percent or more of the foliage was scorched.

Measurements

In late September through early October of 2003, 2004, and 2005, we chose three saplings per plot from the outer two rows of each treatment plot and flagged them. Saplings were randomly chosen from each of three 1/3 percentiles of sapling total tree height per plot. In 2003 and 2004, the flagged saplings were used for destructive sampling of both aboveground biomass and root biomass. In 2005, the flagged saplings were used for determination of root biomass.

The groundline diameter and total height of all saplings in each measurement plot were quantified in winter 2003, 2004, and 2005. We measured groundline diameter and total height of the flagged saplings destructively sampled in 2003 and 2004, and determined total aboveground dry weight after foliage, branches, and stems had been dried to equilibrium at 70 °C. Regression equations to predict total aboveground dry weight as a function of groundline diameter and total height were constructed as described by Sword Sayer and others (2006). With the measurement plot growth data, these equations were used to predict the total aboveground biomass of all saplings in the measurement plots in 2003, 2004, and 2005. Aboveground biomass (AGB) was expressed as megagrams (Mg) per hectare (ha).

Three soil cores (6.5 cm diameter) were extracted 0.5 m from the base of the stem of each flagged sapling using a metal coring device (Veihmeyer 1929). Core locations were random around the circumference of the sapling. Cores were partitioned into 0- to 20-cm and 20- to 30-cm soil depth increments, pooled by depth increment and sapling, and refrigerated until processing. Root biomass was removed from soil samples by wet sieving (1-mm^2 mesh). Pine roots were distinguished from non-pine roots based on diameter, color, plasticity, and the appearance of lateral roots and ectomycorrhizae. Using digital calipers, pine roots were separated by diameter into three categories: (1) very fine plus fine, (2) small, and (3) medium and larger (Sutton and Tinus 1983). Very fine plus fine roots were 0- to 2-mm diameter, and small roots were >2- to 5-mm diameter at the midpoint of the main lateral root. Medium and larger roots were >5 mm diameter. Categories of pine roots were further separated into live and dead categories based on color, plasticity, the appearance of lateral roots and ectomycorrhizae, and adherence of the cortex to the vascular cylinder. Very fine plus fine and small pine roots were oven-dried (70 °C) to equilibrium, ground in a Wiley mill (1-mm^2 mesh), and combusted (450 °C, 8 h) to obtain ash-free dry weights. Very fine plus fine and small pine ash-free root biomass, medium and larger pine root biomass, and non-pine root biomass at the 0- to 20-cm and 20- to 30-cm soil depths were expressed as milligrams (mg) of root tissue per cubic centimeter (cm^3) of soil volume. Data were summed to obtain values of very fine plus fine pine root biomass that was live or dead (LiDeFi), and very fine plus fine and small pine root biomass that was live (LiFiSm), dead (DeFiSm), and live or dead (LiDeFiSm).

Statistical Analysis

Root biomass categories were transformed to square root or natural logarithm (ln) values to establish normality, and evaluated by analyses of variance using a split plot in space, randomized complete block design with five blocks (SAS 2000). Depth was the whole plot effect and vegetation management was the subplot effect. Effects were considered significant at $P \leq 0.05$ unless otherwise noted. Means were compared by the Tukey test and considered significantly different at $P \leq 0.05$ unless otherwise noted.

Plot AGB was transformed to ln values and non-pine root biomass, LiDeFi pine root biomass, and LiDeFiSm pine root biomass were transformed to square root values to establish normality. With ln (AGB) as the covariate, transformed values of non-pine root biomass, and LiDeFi and LiDeFiSm pine root biomass at the 0- to 20-cm and 20- to 30-cm soil depths were evaluated by analyses of covariance using a randomized complete block split plot in time design with five blocks (SAS 2000). Year was the whole plot effect and vegetation management was the subplot effect. Effects were considered significant at $P \leq 0.05$ unless otherwise noted. Means were compared by the Tukey test and considered significantly different at $P \leq 0.05$ unless otherwise noted.

RESULTS

The variation associated with pine root biomass in the >2- to 5- and > 5-mm diameter categories precluded several root biomass variables and their transformed values from being normally distributed. After square root or ln transformations, seven root biomass variables were normally distributed. Analyses of variance and covariance were conducted for the following root biomass variables: non-pine root biomass, and LiFi, DeFi, LiDeFi, LiFiSm, DeFiSm, and LiDeFiSm pine root biomass.

Root biomass variables were significantly affected by depth (table 1). Averaged across all years, non-pine and pine root biomass in the 20- to 30-cm soil depth were approximately 29 and 35 percent of that in the 0- to 20-cm soil depth, respectively. In 2003, 2004, and 2005, non-pine root biomass was significantly affected by vegetation management treatment with less on the H plots compared to the C and B plots (fig. 1A). In 2003 and 2004, pine root biomass was significantly affected by vegetation management treatment. Values of LiFiSm and LiDeFiSm pine root biomass were greater on the H plots compared to the C and B plots (fig. 1C). In 2004, LiFi, DeFi, and LiDeFi pine root biomass were

Table 1—Probabilities of a greater *F*-value for the non-pine and pine root biomass of restored longleaf pine saplings in central Louisiana for three consecutive years in response to three vegetation management treatments

		Root biomass category						
Source of variation	df[a]	Non-pine	Live, pine, 0-2 mm diameter	Dead pine, 0-2 mm diameter	Live+dead, pine, 0-2 mm diameter	Live, pine, 0-5 mm diameter	Dead, pine, 0-5 mm diameter	Live+dead, pine, 0-5 mm diameter
				2003				
Block (B)[b]	4	0.2577	NS[d]	NS	NS	0.3301	NS	0.4227
Depth (D)	1	0.0206				0.0568		0.0452
B x D	4	0.4434				0.0699		0.1794
Treatment (T)[c]	2	0.0145				0.0020		0.0045
T x D	2	0.9176				0.2771		0.6117
				2004				
B	4	0.2732	0.1806	0.7376	0.3068	0.3391	NS	0.3345
D	1	0.0001	0.0010	0.0025	0.0009	0.0026		0.0033
B x D	4	0.2012	0.5861	0.7587	0.5004	0.4694		0.3347
T	2	0.0002	0.0013	0.0015	0.0003	0.0044		0.0006
T x D	2	0.0018	0.3935	0.7355	0.5625	0.9744		0.0728
				2005				
B	4	0.1402	0.3238	0.2154	0.1022	0.9521	0.3338	0.8999
D	1	0.0026	0.0005	0.0008	0.0001	0.0026	0.0006	0.0018
B x D	4	0.6895	0.7977	0.6277	0.9420	0.4834	0.7907	0.4122
T	2	0.0727	0.3678	0.2813	0.3053	0.1330	0.2621	0.1147
T x D	2	0.8623	0.1779	0.2186	0.1953	0.1344	0.3896	0.1305

[a] df: degrees of freedom
[b] Analyses were conducted with data transformed to their square root or natural logarithm values.
[c] Treatments were no vegetation management (C), vegetation management by repeated prescribed fire (B), and vegetation management by herbicide application (H).
[d] NS: Not statistically significant

greater on the H plots compared to the C and B plots (fig. 1B), and DeFiSm pine root biomass was greater on the H plots compared to the C plots (fig. 1C). In 2005, LiDeFi and LiDeFiSm pine root biomass exhibited non-significant trends similar to those found in 2003 and 2004.

Non-pine root biomass at the 0- to 20-cm soil depth and LiDeFi pine root biomass at the 20- to 30-cm soil depth, adjusted by ln (AGB), were significantly affected by year (table 2). Adjusted non-pine root biomass at the 0- to 20-cm soil depth in 2004 and 2005 (4.09 ± 0.02 mg/cm^3) was more than twice that in 2003 (2.02 ± 0.03 mg/cm^3), and adjusted LiDeFi pine root biomass at the 20- to 30-cm soil depth in 2004 (0.056 ± 0.002 mg/cm^3) was 69 percent less than that in 2003 (0.182 ± 0.002 mg/cm^3). Although year had a marginally significant effect on LiDeFi pine root biomass at the 0- to 20-cm soil depth (P = 0.0590), means were not significantly different by the Tukey test.

Non-pine root biomass at the 0- to 20-cm soil depth and LiDeFiSm pine root biomass at the 20- to 30-cm soil depth, adjusted by ln (AGB), were significantly affected by vegetation management treatment (table 2), but means were not significantly different by the Tukey test. Vegetation management treatment had a marginally significant effect on adjusted LiDeFi pine root biomass at the 20- to 30-cm depth (P = 0.0643). Adjusted LiDeFi pine root biomass at the 20- to 30-cm soil depth was 47 percent less on the B plots (0.078 ± 0.001 mg/cm^3) compared to the C plots (0.149 ± 0.002 mg/cm^3) (fig. 2B).

DISCUSSION

Average pine very fine plus fine root biomass (≤ 2 mm diameter) in the 0- to 30-cm soil depth across management treatments and years was 0.3 mg/cm^3 or 30 kg/ha. In comparison to longleaf pine root biomass observations elsewhere, this value is low. For example, depending on age and management activity, longleaf pine stands on sandy soils in southwestern Georgia had 400 to 1 000 kg/ha of pine root

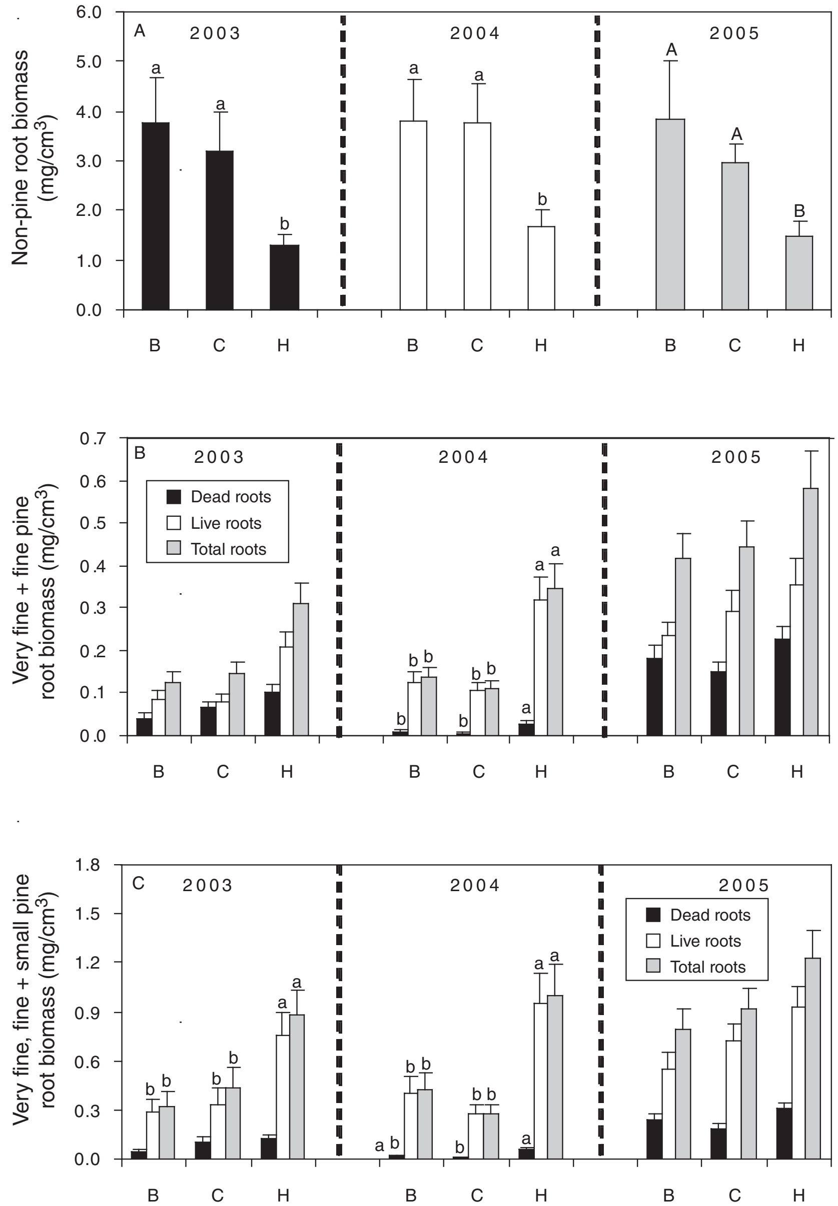


Figure 1—Non-pine root biomass (A), pine root biomass that was 0- to 2-mm diameter (B), and pine root biomass that was 0- to 5-mm diameter in 2003 , 2004, and 2005 in response to no vegetation management (C), vegetation management with repeated prescribed fire (B), and vegetation management by herbicide application (H). Bars represent one standard error of the mean. Means within a year and root biomass category associated with a different lower, or upper case letter are significantly different at $P \leq 0.05$ or $P \leq 0.10$, respectively, by the Tukey test.

biomass ≤ 2 mm in diameter in the 0- to 30-cm soil depth (Carter and others 2004, Jones and others 2003). On sandy soils in north central Florida, Brockway and Outcalt (1998) reported a range of pine root biomass ≤ 5 mm in diameter plus non-pine fine root biomass in the 0- to 20-cm soil depth between 500 and 4 000 kg/ha, depending on distance from the gap edge of mature longleaf pine. In a 65 year old longleaf pine stand on a silty soil in central LA, Sword and Haywood (1999) reported a value of approximately 3 g/dm^3 or 3 000 kg/ha at the 0- to 20-cm soil depth for pine root biomass ≤ 2 mm in diameter. The wide range of fine root biomass values observed for longleaf pine may be attributed to stand age and variability. At our study site, we expect longleaf pine fine root biomass and the uniformity of its distribution to increase as saplings grow into trees and crown closure approaches (Kozlowski and others 1991, Vogt and Persson 1991). The influence of soil resource availability on carbon allocation to fine root production may have also affected longleaf pine root biomass—with more root biomass produced per unit of leaf area on the xeric sites of Georgia and Florida, compared to our mesic study site (Addington and others 2005). Finally, we extracted soil cores for root biomass in late September through early October. At the same time in central Louisiana, longleaf pine root biomass in the surface soil may have been low due to the influence of seasonal drought on fine

Table 2— Probabilities of a greater F-value associated with the analyses of covariance of non-pine root biomass, sapling longleaf pine very fine and fine root biomass that was live or dead (L+D/0-2), and sapling longleaf pine very fine, fine, and small root biomass that was live or dead (L+D/0-5). Data were collected at two depths and in three consecutive years in central Louisiana in response to three vegetation management treatments.

			Root biomass variable		
Source of variation	df[a]	Depth	Non-pine	L+D/0-2	L+D/0-5
Covariate[b]	1	0-20 cm	0.1137	0.0040	0.0053
Block (B)[c]	4		0.8351	0.4691	0.5843
Year (Y)	2		0.0369	0.0590	0.6803
B x Y	8		0.1266	0.8265	0.0457
Treatment (T)[d]	2		0.0259	0.2520	0.3834
Y x T	4		0.9151	0.5689	0.1496
Covariate	1	20-30 cm	0.8114	0.0058	0.0262
Block (B)	4		0.4764	0.8377	0.4943
Year (Y)	2		0.1110	0.0139	0.1633
B x Y	8		0.2160	0.3702	0.2447
Treatment (T)	2		0.6770	0.0643	0.0451
Y x T	4		0.8076	0.1529	0.0959

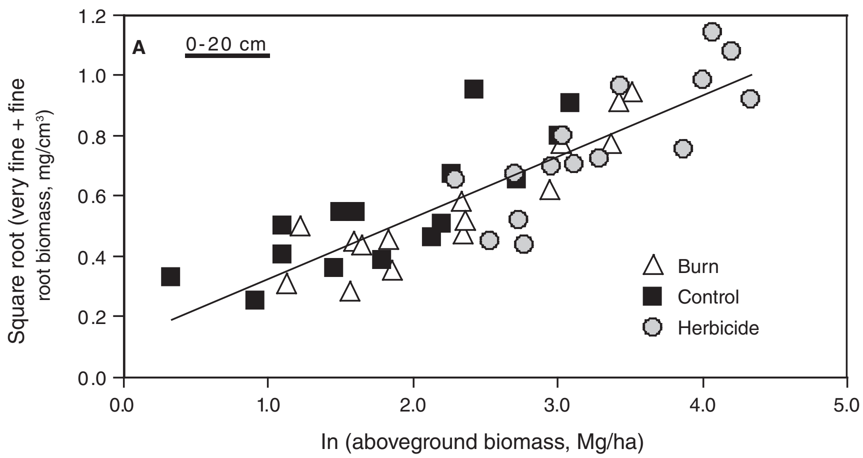
[a] df: degrees of freedom
[b] The covariate was the natural logarithm of plot aboveground biomass (Mg/ha).
[c] Analyses were conducted with data transformed to their square root or natural logarithm values.
[d] Treatments were no vegetation management (C), vegetation management by repeated prescribed fire (B), and vegetation management by herbicide application (H).

root survival and growth (Marshall 1986, Sword Sayer and Haywood 2006).

The year-to-year variation that we observed in adjusted non-pine root biomass at the 0- to 20-cm soil depth and adjusted pine root biomass at the 20- to 30-cm soil depth suggests that root processes were responsive to environmental and/or physiological factors that differed among years. An obvious factor that may have controlled root activity is climate. Precipitation was greater in 2004 (196 cm) than in 2003 (117 cm) and 2005 (109 cm) (SRCC 2007). Further, precipitation between March and August of 2004 was 47 percent greater than normal, while precipitation between March and August of 2003 and 2005 was 34 and 50 percent below normal, respectively. The positive non-pine root biomass response at the 0- to 20-cm soil depth associated with elevated rainfall in 2004 and maintenance of this belowground biomass in 2005 demonstrate one mode by which understory vegetation may have capitalized on an opportunity to further its establishment belowground (Jones and others 2003). Because year did not significantly affect pine root biomass at the 0- to 20-cm soil depth, however, our data present no evidence that soil resource exploitation by non-pine roots affected pine root biomass.

Elevated precipitation in 2004 also could have been responsible for reduced values of adjusted LiDeFi pine root biomass at the 20- to 30-cm soil depth in 2004 compared to 2003. The peak period of pine root production in central Louisiana generally begins in April and continues through July (Sword Sayer and Haywood 2006, Sword Sayer and Tang 2004). Monthly rainfall in May and June of 2004 was 13 and 15 cm, respectively, which is greater than twice the normal rainfall (SRCC 2007). During the early portion of the peak period of root growth, soil in the 20- to 30-cm soil depth may have been saturated due to the presence of a perched water table and the inherently low hydraulic conductivity of this silty soil (Kerr and others 1980). New pine root growth in 2004 may have been restricted to the 0- to 20-cm soil depth until adequate transpiration and soil water loss created a more aerobic soil environment at the 20- to 30-cm soil depth. By 2005, residual effects of this soil saturation theory were absent with similar adjusted LiDeFi pine root biomass in 2003 and 2005 at the 20- to 30-cm soil depth.

Carter and others (2004) observed a reduction in longleaf pine fine root biomass at the 0- to 30-cm soil depth over a 7 month period after the loss of approximately 95 percent of the foliage by artificial crown scorch in June. Similarly, we found that 80 to 100 percent crown scorch was associated with lower adjusted LiDeFi pine root biomass at the 20- to 30-cm



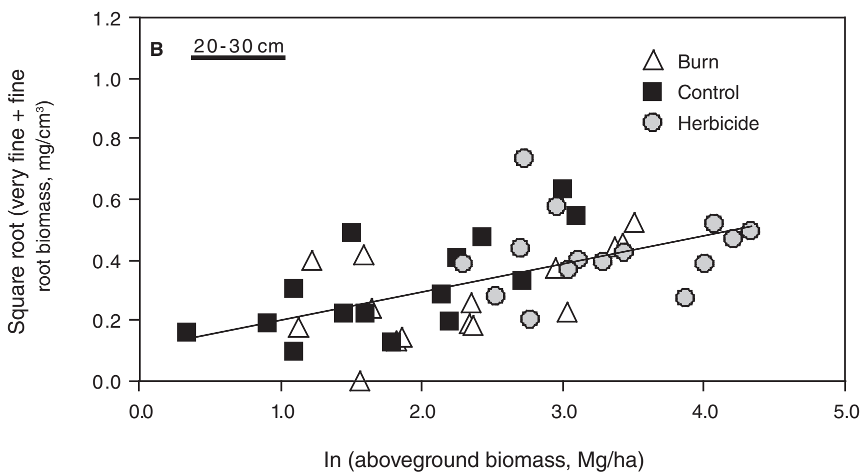


Figure 2—Relationship between the natural logarithm of predicted aboveground biomass and the square root of pine root biomass that was 0- to 2-mm diameter at the 0- to 20-cm depth (A), and the 20- to 30-cm depth (B), in response to no vegetation management (Control), vegetation management with repeated prescribed fire (Burn), and vegetation management by herbicide application (Herbicide). Data are plot means in 2003, 2004, and 2005.

soil depth. We did not, however, observe a similar response at the 0- to 20-cm soil depth. Dissimilar pine root biomass responses to prescribed fire at different soil depths may be attributed to the rate at which root growth recovered during the several month period after prescribed fire in May. With the reestablishment of foliage after fire, carbon allocation to and within root systems controlled root production. We found an average of 69 percent more fine root biomass in the 0- to 20-cm soil depth compared to the 20- to 30-cm soil depth, suggesting that the metabolic activity and, therefore, sink strength in the 0- to 20-cm soil depth was greater than that in the 20- to 30-cm soil depth. Greater sink strength in the 0- to 20-cm soil depth compared to the 20- to 30-cm soil depth may have benefited recovery of fine root biomass in the 0- to 20-cm soil depth, so that several months later fine root biomass was not different between the B and C plots at this depth. In contrast, less fine root biomass at the 20- to 30-cm depth on the B plots—compared to the C plots—may have been a function of both a limited carbohydrate supply for root metabolism and low sink strength.

Our results provide insight regarding improvements to our experimental methodology. Because we observed a reduction in fine root biomass only at the 20- to 30-cm depth, and this may be attributable to variation in root system sink strength and future root biomass observations after crown scorch, we will conduct future observations at a higher resolution. Frequent observations that start immediately after prescribed fire, rather than one observation made several months after prescribed fire, will improve our ability to discern root biomass responses throughout the period of foliage reestablishment and as the seasonal change in sink strength of different parts of the root system. Further, it appears that evaluation of longleaf pine roots larger than 2 mm diameter at our study sites requires a larger sample size (i.e., n = 3). Because the time required to process longleaf pine root biomass collected by soil coring precludes an increase in sample size, future research will employ a different sampling method. Finally, the potential influence of climate on non-pine and pine root biomass in our study suggests that key climate and soil measurements should accompany future longleaf pine root biomass observations. With this information, longleaf pine root biomass could be evaluated as a function of environmental stimuli; the resolution of treatments effects could then be improved.

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FUEL LOADING AND FIRE INTENSITY—EFFECTS ON LONGLEAF PINE SEEDLING SURVIVAL

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Abstract—Modeling silvicultural practices after natural disturbance, with a particular focus on the use of fire and small canopy openings, may be particularly appropriate in longleaf pine (*Pinus palustris* Mill.) woodlands managed for multiple age classes and over long time scales. However, information about the effects of litter accumulation and fire temperatures on longleaf seedlings is inconsistent. This study examined the effects of season of burn, pine litter loading, and subsequent fire intensity on survival and growth of longleaf seedlings. For both fire seasons, mortality increased over time and was highest for the smallest grass stage seedlings and in the high litter treatment. Litter levels affected fire intensity but had relatively minor effects on subsequent growth of surviving seedlings, but season of burn did affect seedling mortality. The grass and herbaceous fuels of the low litter treatment did not burn during either season, indicating the importance of pine needles for fuel.

INTRODUCTION

Modeling silviculture after natural disturbance has become a popular concept in forest management. With the resurgence of interest in restoring and managing longleaf pine (*Pinus palustris* Mill.) ecosystems in the Southeast, the natural disturbance model may be particularly applicable. Historically, frequent small-scale natural disturbances have played a significant role in maintaining the longleaf forest structure and composition, resulting in a heterogeneous canopy structure and subsequent variation in pine litter deposition (Mitchell and others 2006). Initial restoration efforts have focused both on establishing longleaf pine regeneration and reintroducing fire, the dominant historic disturbance, into these systems. However, results from studies comparing the effects of litter accumulation on fire temperature and the subsequent effects on seedling growth and survival are inconsistent, and generally do not consider different levels of needle litter accumulation in conjunction with groundcover.

We know that longleaf pine seedlings are extremely tolerant of fire once they are well established and have achieved a minimum size (Croker and Boyer 1975). They are not, however, fireproof and the use of prescribed fire can affect longleaf seedling survival and growth. Several factors can affect seedling response to fire, including growth stage (both within the annual cycle and long-term), vigor and competitive status, and the fuel loading around the seedlings. The relative importance of these individual factors is not easy to determine, however, due to the number of interactions between them. For instance, natural longleaf pine regeneration is typically found in larger openings away from adult trees due to the overstory competition with seedlings as well as the interaction of seedlings with fire. The overstory affects resources such as light availability and has a direct effect on seedling growth (Battaglia and others 2003, McGuire and others 2001, Palik and others 1997). Survival, however, is often related to the fire resistance of grass stage seedlings, and increased litterfall near mature trees leads to higher fire temperatures (Glitzenstein and others 1995, Williamson and Black 1981) such that a greater seedling size is needed to survive fire when close to adults (Boyer 1974, Bruce 1950). Further, seedling response is rarely evaluated in response to operational prescribed fire due to the lack of controls and the high variability. Yet, it is the response of longleaf regeneration to operational fires that is important for long-term sustainable management in these forests.

Our objective for this study was to examine the survival and growth response of longleaf pine seedlings to operational prescribed fire conducted in both the dormant and growing seasons. Specifically, we: 1) examined the correlation between fuel loading and fire temperature; 2) quantified the variation in fire temperature with height; 3) examined interactions between seedling size and fuel loading on survival and growth; and 4) evaluated the effectiveness of grass fuels in the absence of pine litter.

METHODS

Study Site

The research was conducted at the Joseph W. Jones Ecological Research Center at Ichauway, an 11 600 ha reserve in southwest GA. The climate is subtropical with mean daily temperature ranging from 5 to 17 °C in the winter and 21 to 34 °C in the summer (Goebel and others 2001). Annual precipitation averages 132 cm, evenly distributed throughout the year. Over 7 000 ha of the site have an overstory of 75 to 95 year-old naturally regenerated second-growth longleaf pine and a species-rich groundcover, including wiregrass (*Aristida stricta* Michx.) (Kirkman and others 2001).

The operational prescribed fires were conducted at two different times of the year in similar burn units. Both units had 1-year rough and had been managed with frequent fire for over 50 years. Soils were moderately-well to well-drained Ultisols. The growing season burn unit was 17 ha in size while the dormant season burn unit was 160 ha. Treatment plots in both burn units were located in canopy gaps with abundant natural regeneration. Average basal area of the overstory for the treatment plots was 1 m^2/ha. Groundcover in the plots was dominated either by wiregrass or by slender bluestem (*Schizachyrium tenerum* Nees).

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Experimental Design and Sampling

Operational prescribed fires were conducted in both the growing season (July 2004) and the dormant season (January 2005) using strip headfire ignition techniques. Within the burn units for each season of burn we established 3 replications of 3 fuel treatments (i.e., n=9 plots per season). The treatment plots were 7 by 14 m (approximately 0.01 ha) and were located to include a size range of naturally regenerated longleaf pine seedlings. The three plots in each replicate were constrained as to location (they needed to be relatively close together) to facilitate the use of data recorders for the thermocouple set-up (see details below). However, treatments were assigned randomly to the three plots within a replicate.

The three fuel treatments were 1) low litter treatment where the pine straw was raked from the plots, 2) control or ambient pine litter where the existing litter was left intact, and 3) high litter treatment where additional pine straw was added to the plot. The raked pine litter from the low litter treatments was added to the high litter plots to roughly double the amount of pine straw in the high litter treatment, resulting in approximately 0, 1x and 2x levels of pine litter in the treatments.

Fire temperatures were monitored in the treatment plots using thermocouple arrays. Fire temperatures were estimated at three heights (ground or 0, 1, and 2 m) at 2 locations within each plot using K-type thermocouples (6 thermocouples per height and treatment combination, 54 total) attached to galvanized conduits placed 3.5 m from plot edges. Thermocouples were attached to multiplexors using type K AWG 20 thermocouple wire (maximum temperature 900 °C). Multiplexors were attached to Campbell dataloggers and installed in heavy-duty toolboxes which were buried at the center of each replicate block under approximately 30 cm of soil just prior to burning. Thermocouples were sampled at 3 second intervals, and residence times above a threshold temperature of 70 °C calculated.

All seedlings within the plots were mapped and tagged prior to the fire treatments. In addition, each seedling was measured for root collar diameter (RCD) and height to the base of the terminal bud, and a height class group assigned based upon this height measurement. Height classes were assigned to seedlings as follows: 1 = small grass stage (< 0.2 m); 2 = grass stage (< 1 m); 3 = rocket stage (in active height growth, < 2m); and 4 = sapling (> 2 m tall with RCD < 15 cm). Initial seedling mortality was assessed two weeks after the fire application. Seedling growth (basal diameter and height) were measured along with survival at the end of the first growing season following the fire (October 2004 and 2005 for growing season and dormant season, respectively) and at the end of the 2006 growing season.

Data were analyzed in SAS (v. 9.1 for Windows, SAS Institute, Inc., Cary, NC) using SAS/STAT. Seedling growth data were analyzed using Proc GLM, while categorical data (survival, residence time) were analyzed using Chi-square tests for independence. Statistical significance was assessed at $\alpha = 0.05$ level.

RESULTS AND DISCUSSION

The fuel treatments did result in different fire characteristics during the operational prescribed fire. Most striking was that the low litter treatments (with pine straw removed) essentially did not burn for either season – the flame front burned up to the plot boundaries on all sides but did not burn at all into the plots. This result was not completely surprising for the growing season fire as the groundcover vegetation was green and succulent. In the dormant season fire, however, the groundcover vegetation was dry and brown yet still did not burn even though wiregrass was the dominant species in these plots. In contrast, the control and high litter treatments had complete fuel removal as the fire front burned through the plots.

Fire intensities, as indicated by maximum recorded temperatures, were in general positively correlated with fuel loadings (fig. 1). Growing season fires were on average hotter than the dormant season fires but there were no statistical differences in maximum observed temperatures between seasons. The patterns of maximum temperature with sensor height followed expected trends, especially when averaged across fuel treatments (fig. 1), but the patterns for the dormant season fire with height were more variable.

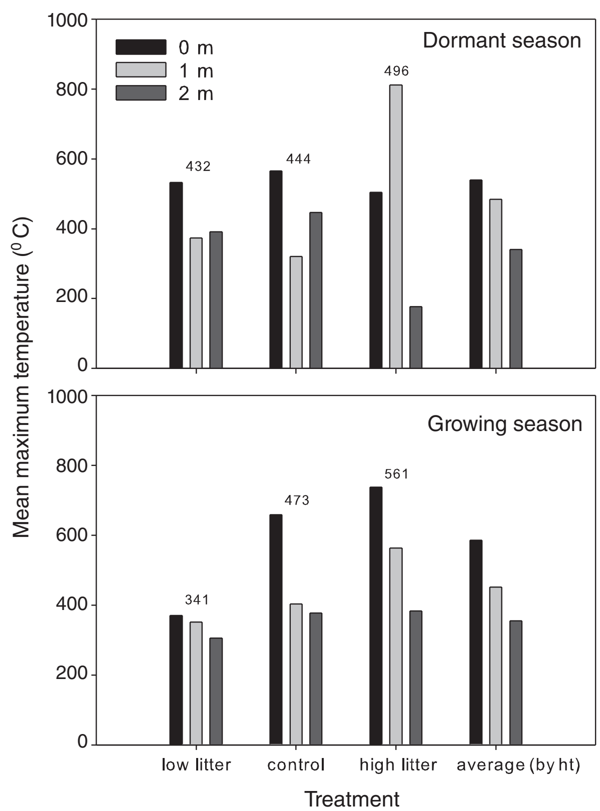

Figure 1—Mean maximum temperature measured at each sensor height for each fuel loading treatment and averaged across treatments. Numbers over bar groups represent the maximum temperature measured across heights. Upper graph is for dormant season burn; lower graph is for growing season burn. Although some patterns are apparent with increasing fuel loads and sensor height, no statistical differences were detected.

For plant tissue death, it is not only the temperature to which the tissue is exposed that is important, but also the length of that exposure, also known as the residence time. The threshold temperature for instantaneous (i.e., less than 1 second) plant tissue death is generally thought to be 60 °C (Wright 1970), but this value varies somewhat by species with the value for longleaf pine being slightly higher (Wade and Johansen 1986). We calculated the residence time for temperatures above 70 °C as this will certainly result in tissue death. The results in figure 2 illustrate the variability in residence times with sensor height and fuel treatment. The most obvious result is that the growing season fire had much longer residence times above 70 °C than was measured for the dormant season fire. This result is not surprising given the much higher air temperatures during the growing season and the reduced heating required to reach the threshold temperature. A pattern of increasing residence time with increasing fuel loading only holds true for the ground-level sensor in both seasons (fig. 2). The more variable pattern at the 1 and 2 m heights is possibly due to eddy currents moving heat in variable patterns above the flame front (Clements and others 2006), where it is detected by the thermocouples. Although there were not consistent patterns of increasing residence time with increasing fuel loading across the sensor heights for either season, the residence times were statistically different between heights as indicated by a Chi-square test ($p<0.0001$ for both seasons).

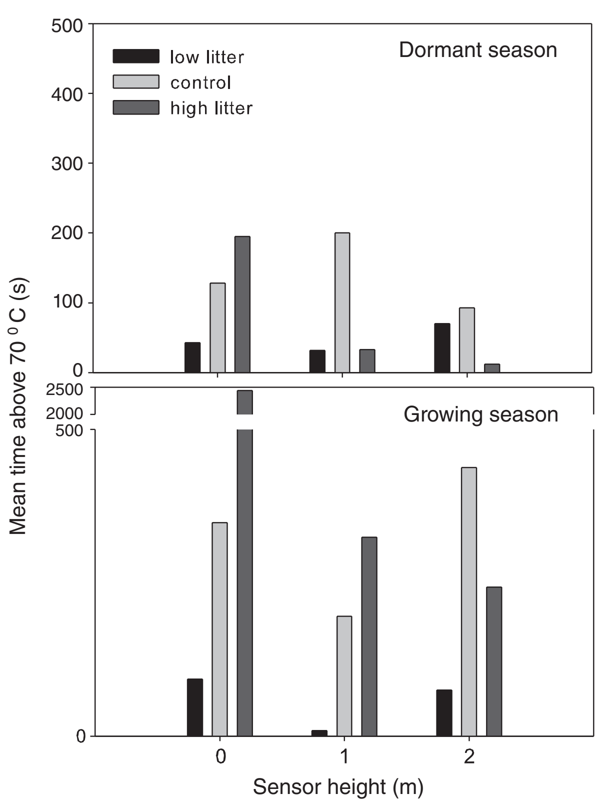

Figure 2—Average residence time above 70 °C by fuel loading treatment and sensor height. Note scale differences between upper (dormant season) and lower (growing season) graphs. Residence time was statistically different between sensor heights (χ^2 $p<0.0001$) for both seasons but was not statistically different between fuel treatments.

Seedling survival was reduced by higher fuel loading, both at the end of the first growing season and at the end of the 2006 growing season (fig. 3); the survival rates for the low litter and control treatments were not statistically different, but both were statistically greater ($p<0.001$ by χ^2 test) from the high litter survival rate when data were pooled between growing seasons for both measurement times (fig. 3a).
In comparing the survival by season of burn (fig. 3b) the survival rate from the growing season was significantly lower ($p<0.0001$ by χ^2 test). Examining the data more closely indicated that most of the mortality was concentrated on the smallest seedlings (those in height class 1), and that the mortality tended to increase with fuel loading at both measurement times (fig. 4a). This result is similar to that found by Grace and Platt (1995) for very small longleaf pine seedlings experiencing different levels of pine needle loading due to canopy density. Perhaps more interesting is that mortality increased with time for all fuel treatments (fig. 4a), even though the low litter treatment plots did not burn. This result indicates that direct fire effects are not the only cause of mortality detected in this study, though we do not know specifically what those other causes might be. Similar to the results for fuel treatment, the growing season fire had a lower survival rate in comparison to the dormant season fire at both measurements (fig. 4b).

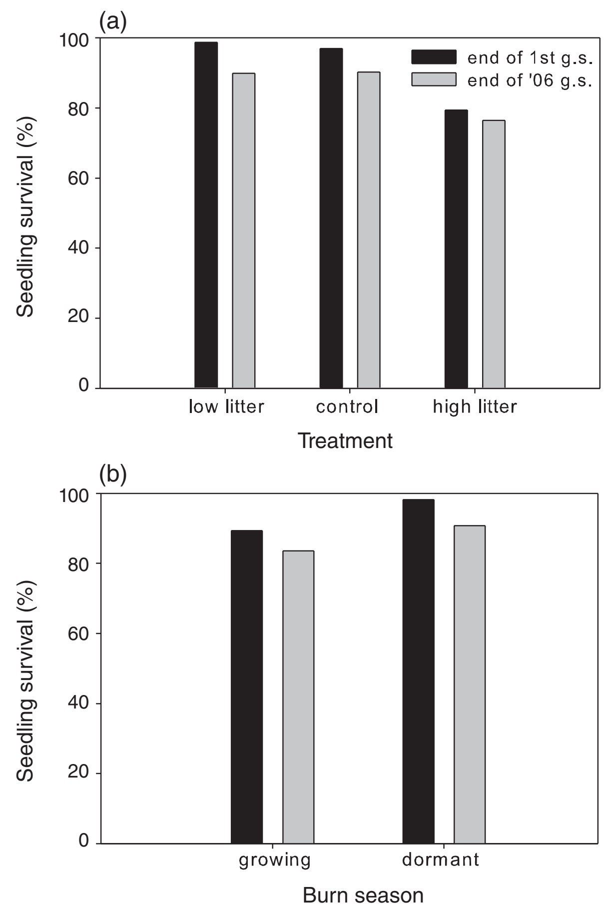

Figure 3—Percent survival for all seedling size classes, measured at the end of the first growing season post-fire and the end of the 2006 growing season, by (a) fuel loading treatment and (b) season of burn. Chi Square tests showed significant differences between fuel treatments ($p<0.001$) and burn seasons ($p<0.0001$) at both time periods.

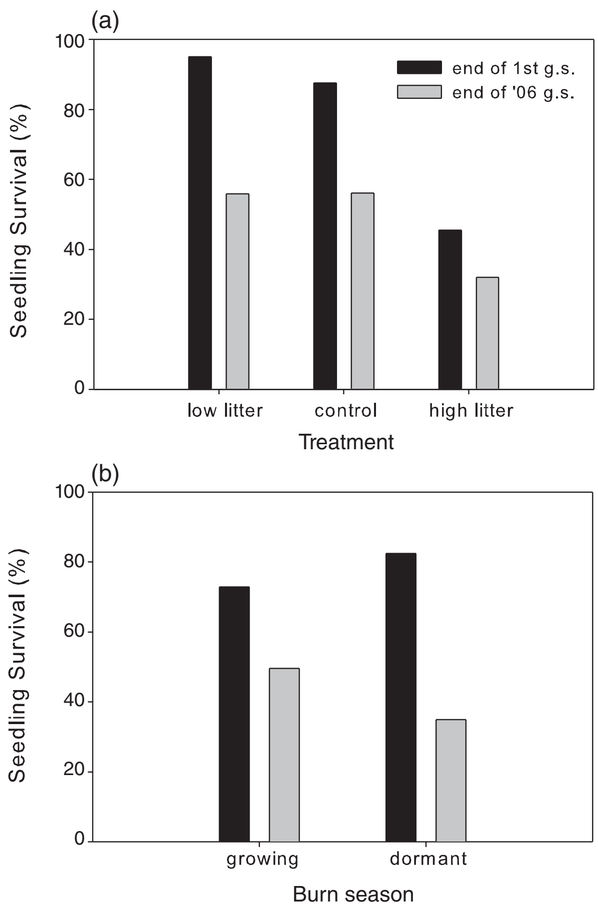

Figure 4—Percent survival for smallest seedling size class (small grass stage, height class 1, <0.2 m), measured at the end of the first growing season post-fire and the end of the 2006 growing season, by (a) fuel loading treatment and (b) season of burn. Chi Square tests indicated significant differences for the fuel loading ($p<0.0001$) and fire season ($p<0.01$) at both time periods.

Growth responses to fuel treatment and fire season were mixed. There were no significant differences ($\alpha = 0.05$) in height growth at the end of the 2006 growing season either by fuel loading or season of burn, though there appears to be a trend of decreasing height growth with increased fuel (fig. 5a), and height growth following the dormant season burn was slightly greater (fig. 5b). Given the very small RCD values recorded for many of the smallest seedlings it was difficult to calculate directly positive RCD growth; instead, we compared initial and final RCD to assess if the treatments led to any differences in RCD. With this data limitation, there was no statistical or apparent response in RCD growth with fuel loading (fig. 6). The effect of burn season on RCD could not be assessed in this instance because the growing season and dormant season populations had significantly different average RCDs at both the initial measurement and the final measurements (data not shown). The analysis of both the height and RCD data was complicated by the large range of seedlings sizes measured in the study and the resulting high variability.

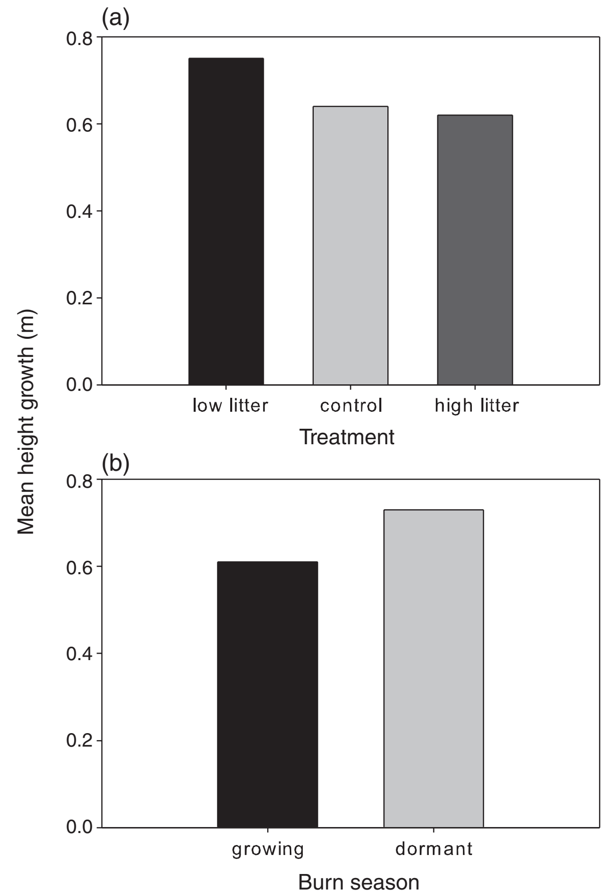

Figure 5—Mean height growth response for all seedling sizes by (a) fuel loading treatment and (b) season of burn. No statistical differences were found between treatments or seasons using ANOVA procedures.

The results from this study present a case study examining the effects of operational prescribed fire on seedling mortality and growth with varying levels of fuel loading. The results should not be extrapolated broadly to all prescribed fire in longleaf pine forests, but they do begin to address gaps in our knowledge of fire and longleaf seedling response. Of particular interest is the fine-scale variability in fuel loading found under a natural longleaf pine canopy and the potential influence of this fuel variability on seedling demography (Mitchell and others 2006).

SUMMARY

1. Pine fuels (needles) are necessary for fires to carry well in these forests, particularly in natural gaps and even with the presence of wiregrass and in the dormant season when vegetation is cured.
2. Prescribed fire did have an effect on longleaf seedling and sapling mortality and growth, but fire was not the only influence and many factors interact to determine the response to fire.
3. Higher levels of pine fuel loading generally led to more intense fires and higher seedling mortality.

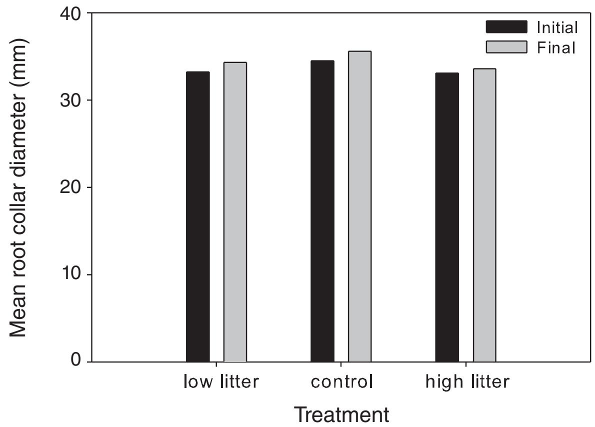

Figure 6—Average root collar diameter (RCD) by fuel loading treatment at beginning of study and at the end of the 2006 growing season. ANOVA tests found no statistical differences between treatments at either measurement time.

4. Contrary to our initial assumption we did not detect any significant seasonal differences in seedling response to prescribed fire.
5. Small seedlings are much more likely to die following the application of prescribed fire, but fire is not the only cause of this mortality as delayed mortality occurred in low litter plots that did not carry fire.
6. More controlled experiments are necessary to determine the relationships between fuel loading and fuel bed characteristics and seedling growth response and demography.

ACKNOWLEDGMENTS

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Forest Health and Fire

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FOREST SOIL RESPONSE TO FUEL REDUCTION TREATMENTS IN THE SOUTHERN APPALACHIAN MOUNTAINS

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Abstract—The National Fire and Fire Surrogate Study (FFS) was established to monitor the impacts of fuel reduction treatments (prescribed fire-only, mechanical fuel reduction-only, and a combination of prescribed fire and mechanical fuel reduction) on a host of ecosystem properties at 13 sites across the United States. Treatment impacts were monitored on the Southern Appalachian Mountain FFS site for three to four years following treatment. Control and treatment means for forest floor C:N ratio, soil extractable calcium, and the Ca:Al molar ratio differed one to two years posttreatment. These differences were not noted three to four years posttreatment, but differences were noted for soil extractable iron and soil pH. Results from this analysis suggest that these treatments were applied under the appropriate conditions and guidelines to conserve forest soil resources.

INTRODUCTION

In 2002, 7.2 million acres of forested land burned in seven of the western United States, accounting for the deaths of 23 firefighters and damage to 852 structures. The fire suppression efforts that year cost more than $1 billion (USDA Forest Service Position Paper 2003). In response to rising concerns over wildfire hazard and a desire to restore forest structure and function that may have been altered by close to a century of fire exclusion, the National Fire and Fire Surrogate Study was begun in 1999 to gather a more broad understanding of the effects of fuel reduction treatments on ecosystem properties. This research stretches across 13 study sites around the country and at each site, some use of prescribed fire and harvesting, alone and in combination, is being conducted. Soil resources are one of the many ecosystem components of interest.

Various reports have been published regarding the effects of prescribed fire, harvesting, and a combination of the two on soil resources. The range of fire-induced changes to soil properties and processes is quite varied, depending largely on fire intensity, temperature, vegetation type and amount, soil moisture, and other factors (Wells and others 1979). Increases, decreases, and nonsignificant changes to soil biological, chemical, and physical properties have been documented extensively on a site-by-site basis based upon these factors in response to fire. As a whole, prescribed fires have been found to cause minimal changes to soil resources (Johnson and Curtis 2001, Van Lear 1985). The nature of fire intensity in the southern United States is particularly dominated by understory (Coastal Plain, Piedmont) and mixed fires (Southern Appalachians) that do not consume large quantities of organic matter or expose large amounts of mineral soil (Stanturf and others 2002).These effects should be considered on a site-by-site basis, however.

Harvesting elicits a response similar to burning based upon the extent, method, and timing of harvesting. Soil physical properties tend to be the most sensitive properties with regard to harvesting. Soil bulk density has been found to increase in several studies following harvesting, largely due to the use of mechanized equipment. Other considerations should be given to the amount of material removed during harvesting and the amount of residual materials that are left to decompose after harvesting. Zhou and others (1998) found that residues left in place after harvesting had little influence on the potential N mineralization rates in the soil, but Merino and others (1998) found that the removal of logging residues reduced N mineralization following both whole-tree harvesting and stem-only harvesting of pine forests in Spain.

Burning alone and harvesting alone are desirable to some degree for the reduction of fuels. However, the heavy fuel-loading present in many stands throughout the U.S. calls for a combination of treatments, such as both thinning and burning (Stanturf and others 2002). Many studies have evaluated the effects of prescribed fire and harvesting individually, but not as many have examined the effects of a combination treatment, particularly for the longer term. Much like the two treatments individually, several studies show mixed results for the combination of thinning and burning on N. Knoepp and Swank (1993) suggested that total N and soil NO_3^--N availability were not affected by the felling and burning of pine-hardwood stands in the Southern Appalachian Mountains. They also concluded that an initial pulse of soil NH_4^+-N was seen in as little as 48 hours after treatment and remained elevated up to one year posttreatment. Little leaching losses and movement of N were found as well. Clipping and burning of material was noted by Wells and others (1979) to cause increased N mineralization as well. In this paper, we summarize the response of soil resources for the Southern Appalachian Mountain FFS site for four years posttreatment.

METHODS

Study Area

The Southern Appalachian Mountain study site of the FFS resides on the Green River Game Land in Polk County, North

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Carolina. The Game Land covers 5,841 ha and is managed by the North Carolina Wildlife Resources Commission. Stands are a mixture of oaks, pines, and hickories based on topographic location (Waldrop 2001). Some of the oak species include northern red (*Quercus rubra*), chestnut (*Q. prinus*), white (*Q. alba*), and black (*Q. velutina*). Mountain-laurel (*Kalmia latifolia*) and great rhododendron (*Rhododendron maximum*) are the predominant shrub species. Soils within the Evard soil series (fine, loamy, Typic Hapludults) and Cliffield soil series (loamy-skeletal, mixed, subactive, mesic Typic Hapludults) are characteristic of the area. These well-drained soils are found in mountain uplands (Soil Survey Staff 2005).

Experimental Design and Treatment Descriptions

The treatments proposed by the FFS are prescribed burn-only, mechanical cutting-only, a combination of cutting and burning, and a control. A randomized complete block design was used for this study. Each replicate was a contiguous block of land which helped control any variability among sites. Each treatment area was at least 13 ha in size and basal area ranged from 21 to 31 m2/ha before treatment installation (unpublished data). Stand age ranged from 80 to 120 years (Waldrop 2001). This study site had not been cut in at least 10 years prior to treatment and had not been burned in the previous 5 years.

Cutting operations were conducted from December 2001 to March 2002. This treatment was conducted by chainsaw crews that were contracted to cut all trees greater than 1.8 m tall and less than 10.2 cm diameter breast height (d.b.h.). All shrubs were additionally cut and piles of these materials were kept at less than 1.3 m high. The burning for the burn-only and mechanical and burn treatments of replication 3 was conducted on March 12, 2003. These fires were ignited using strip-headfires and spot fires that produced average flame lengths of one to two m or less. The average flame temperature measured by heat tiles 1 m above ground was 120 ^oC. Flames of up to 5 m with temperatures up to 788 ^oC were measured in localized areas as influenced by topographic position and the intersection of flaming fronts (Tomcho 2004). Average flame lengths for these fires were also 1 to 2 m or less and average flame temperature was around 93 ^oC.

Soil Sampling

Soil sampling took place within ten 20 by 50 m plots that were randomly assigned within each of the replicates for all treatments. These plots were also designated for vegetation measurement for another component of the FFS study. For the determination of O horizon C and N, samples were taken from six 10 by 10 m subplots. These samples were oven-dried at 76 ^oC for 16-24 hours. Six samples at these locations were also collected to evaluate the levels of mineral soil C, N, extractable elements (Al, B, Ca, Cu, Fe, Mg, Mn, P, K, Soluble S, Na, Zn) and pH to the 10 cm soil depth. These samples were oven-dried at 76 ^oC for 16-24 hours. Samples were taken 1 to 2 m outside each of the 10 by 10 m subplots to the 10 cm soil depth to determine soil bulk density at each plot using a Model H Oakfield soil probe for the pretreatment and first posttreatment period. Collection of the pretreatment soils data began in June 2001. In like fashion, samples were collected in 2003 to assess the response for the first posttreatment period. To determine the second posttreatment responses, sampling was conducted in the summer of 2005. Bulk density samples were not obtained in 2005 due to a delay in sampling for some of the areas in 2003.

Soil Processing and Laboratory Analysis

Six O horizon samples for each plot were ground using a Wiley mill with a 2 mm sieve. 20 mL from each of the 6 ground samples were then mixed together in a 120 mL vial to comprise one sample for each plot. The same procedure used for processing the O horizon samples was used to prepare the samples needed to determine mineral soil C, N, extractable elements, and pH levels, except grinding of the mineral soil samples was conducted using a Sawyer mill. Bulk density samples were sorted for rocks and roots before and after drying, as needed. The ovendry weight was then divided by the volume of the soil sample to obtain estimates of bulk density in g/cm^3.

All pretreatment and first posttreatment results were conducted by Brookside Analytical Laboratories in New Knoxville, Ohio. O horizon and mineral soil C and N and soil pH were all completed by the U.S. Forest Service Forestry Sciences Laboratory in Athens, Georgia for the second posttreatment results. Analysis for the second posttreatment soil extractable elements was again contracted to Brookside Laboratories. Regardless of the laboratory used, C and N for the forest floor and mineral soil were determined by the combustion of samples and subsequent measurements conducted by the Perkin-Elmer 2400 Series II CHNS/O Analyzer. The additional element concentrations were determined using Mehlich III methodology and subsequent analysis for each element of interest by ICP-Optical Emission Spectrometry. Soil pH was determined using a 1:1 soil to water solution.

The Ca:Al molar ratio was calculated for each sampling period for both locations. This ratio has been suggested to be a useful tool in determining potential nutrient imbalances. Cronan and Grigal (1995) suggest that there is an increased risk of critical impacts on tree growth and nutrition as this ratio is found to be less than 1.0. Molar weights for both Ca and Al were needed to derive this ratio. The equation for this ratio is as follows:

$$\frac{[(\text{mg Ca/kg soil})/\ (40.01\text{ g Ca/M Ca})]}{[(\text{mg Al/kg soil})/\ (26.98\text{ g Al/M Al})]}$$

Statistical Analyses

To obtain an accurate assessment of the effects of fuel reduction on the soils of this area, several statistical procedures were conducted using SAS (SAS Institute 2002). An analysis of variance (ANOVA) was conducted using the pretreatment data to determine if differences in soil properties existed before treatment installation based on the treatment designations. An analysis of covariance (ANOCOVA) was conducted for both locations to determine the first posttreatment response of the variables, with pretreatment data serving as a covariate. In cases where the covariate proved to be non-significant, it was removed from the analysis and an ANOVA was performed. The second posttreatment period results were also evaluated using ANOCOVA with pretreatment values serving as the covariate. In cases where the covariate was nonsignificant, it was removed and ANOVA was used to compare treatment effects. All comparisons were made at the 0.05 level of significance.

RESULTS AND DISCUSSION

Forest Floor Carbon and Nitrogen

The pretreatment covariate was significantly related to the values obtained for first posttreatment O horizon C and for the C:N ratio, but not for O horizon N. The ANOCOVA means for C and the ANOVA means for N suggest that there were nonsignificant differences among the means of the treatments, but the ANOCOVA mean for the C:N ratio on the mechanical and burn treatment was significantly lower than the means of the other treatments (table 1).

In similar fashion to the first posttreatment results, the pretreatment covariate was not significantly related to the second posttreatment results for O horizon N. No significant differences were detected among the ANOCOVA means for C and for the C:N ratio. The ANOVA means for N also suggested nonsignificant differences. It appears that the overall organic quality of the forest floor has been conserved.

The means of the treatments did not differ from one another when measured for the second posttreatment period. This follows the findings of Wells and others (1971), Knoepp and Swank (1993), and Johnson and Curtis (2001), and suggests that these treatments cause little change to forest floor dynamics. These natural systems are relatively efficient at replenishing the amount of material consumed or displaced by these treatments (Van Lear 1985).

Table 1—Treatment means for soil variables noted to possess significant differences among the treatments during either the first or second post-treatment periods for the Southern Appalachian National Fire and Fire Surrogate study. Means are shown plus or minus the standard error without correction for unequal sample sizes. Significant differences among the means are noted by different letters following means within a row ($\alpha = 0.05$)

	Treatment			
Variable	Control	Burn	Cutting	Cut and Burn
O Horizon C:N				
Pre (p = 0.9062)	36.13a ± 0.76	36.92a ± 0.52	36.35a ± 0.81	37.40a ± 0.79
First (p = 0.0472)	32.10a ± 0.95	31.38a ± 0.82	31.13a ± 0.77	27.49b ± 1.17
Second (p = 0.2171)	25.05a ± 0.56	24.35a ± 0.50	26.53a ± 0.57	24.91a ± 0.54
Calcium (mg Ca/kg soil)				
Pre (p = 0.1557)	319.21a ± 41.73	315.62a ± 37.82	203.55a ± 34.41	215.01a ± 25.40
First (p = 0.0270)	155.83a ± 19.33	123.19ab ± 11.67	100.50b ± 5.96	106.74b ± 7.10
Second (p = 0.4150)*	135.47a ± 23.09	178.97a ± 26.93	135.27a ± 14.26	184.93a ± 31.05
Iron (mg Fe/kg soil)				
Pre (p = 0.0011)	111.01b ± 5.74	105.70b ± 4.19	164.23a ± 8.08	150.28a ± 9.75
First (p = 0.0875)	140.69a ± 7.43	133.44a ± 4.40	121.20a ± 6.96	108.77a ± 3.93
Second (p = 0.0143)	113.36a ± 5.06	105.20a ± 4.00	103.83a ± 4.28	93.38b ± 3.29
Molar Ca:Al				
Pre (p = 0.1041)	0.17a ± 0.02	0.17a ± 0.02	0.10a ± 0.02	0.11a ± 0.01
First (p = 0.0058)	0.11a ± 0.013	0.08b ± 0.008	0.07b ± 0.004	0.07b ± 0.006
Second (p = 0.4781)*	0.07a ± 0.01	0.10a ± 0.01	0.07a ± 0.01	0.10a ± 0.02
Soil pH				
Pre	Not available	Not available	Not available	Not available
First (p = 0.7598)	4.53a ± 0.04	4.60a ± 0.04	4.58a ± 0.04	4.61a ± 0.03
Second (p = 0.0457)	4.72a ± 0.04	4.66ab ± 0.03	4.60b ± 0.03	4.65ab ± 0.03

*=non-significant covariate

Mineral Soil Carbon and Nitrogen

The pretreatment covariate was significantly related to the first posttreatment levels for each of these variables and the ANOCOVA means lead to the assumption of nonsignificant differences among the treatment means. The pretreatment covariate was also significant for the second posttreatment results and the ANOCOVA means suggest non-significant differences among the means of the treatments. The organic fraction of the mineral soil was not significantly altered by these treatments.

Extractable Elements

The pretreatment covariate was significant for all of the first posttreatment results except Na. Significant differences were found among the first posttreatment means for Ca, which appeared to be significantly lower on the mechanical-only and mechanical and burn treatments than the control (table 1). Subsequent differences in the Ca:Al molar ratio were detected as a result of the treatments (table 1).

The pretreatment covariates were not significantly related to the second posttreatment values for B, Ca, Na, and the Ca:Al molar ratio. Significant differences among treatment means were only detected for Fe, which was significantly lower on the mechanical and burn treatment than any of the other treatments (table 1).

When fuels are reduced by harvesting or burning, the reduction of material containing high concentrations of a particular element should be expected to result in declines of that element for some period of time (Wells and others 1971). However, this was not the case for all of these extractable elements with these treatments. The nonsignificant covariates for B and Na suggest the dynamic nature of these elements at any given period of time. The values present for these variables during the pretreatment period were not related to the values present during the second posttreatment period and it appears that additional factors, such as precipitation, decomposition, and organism activity, could play a role in this result.

There is no obvious explanation for the differences in Fe among treatments for the second posttreatment period other than the inherent variability for Fe in any given soil. The Ca:Al molar ratios at each time period for both locations appear to fall well below 1.0, which was suggested to be a critical threshold (Cronan and Grigal 1995). Given that this ratio was lower than 1.0 before treatment and continued to be below that value after the treatments, it appears that these practices do not increase any risk for toxicity or stress that is not already present due to inherent soil properties.

Soil pH

Soil pH was not measured prior to treatment. ANOVA means for soil pH during the first posttreatment period suggest that there were non-significant differences among the means of the treatments (table 1). The first posttreatment values served as the covariate for the second posttreatment results and they were significantly related to these values. Significant differences among the means of the treatments were detected, suggesting that soil pH was significantly higher on the control treatment than the mechanical-only treatment (table 1). This may be due to the fact that mountain-laurel and rhododendron stems were left on the ground and are slow to decompose. The total difference between values for the control and mechanical-only treatments is 0.12, which should not adversely affect regeneration or forest health.

Soil Bulk Density

The pretreatment values were significantly related to the values obtained for the first posttreatment period. Using ANOCOVA means, there were no significant differences among the means of the treatments. Soil bulk density was not measured for the second posttreatment period. Chainsaw-felling of shrubs and understory trees, with and without prescribed burning, caused no significant soil compaction.

SUMMARY AND CONCLUSIONS

The results suggest that the fuel reduction treatments had little effect on forest soil properties two to four years after treatment. Despite the fact that several differences among treatment means were detected during the first posttreatment period, these differences did not result in subsequent differences for the second posttreatment period. These soils are dynamic and variable, which is evident from the non-significant covariates present for many of the analyses and the high variability for many of the variables. Also, control means did not remain static and constant over time. Many of the variables measured are influenced by organism activity, moisture relations, temperature, and a host of other variables. The results suggest that the planning and implementation of these silvicultural treatments conserved forest soil resources at these sites.

At any location with any management objective in mind, an assessment of soil resources should be considered due to their variable nature. Fuel reduction treatments vary with regard to intensity and severity and any given soil may respond differently as a result of the factors affecting soil heating, organic matter removal or consumption, compaction, and other properties. Each site will respond differently and one definitive statement summarizing the effects of fuel reduction on soils for all sites is not practical or realistic. The goal of this project was to summarize the effects of these particular fuel reduction treatments on the soils of the Southern Appalachian Mountains and the analyses suggest that there were minimal effects noticed as a result of these treatments over a brief period of time.

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THIRD-YEAR RESPONSES OF UNDERSTORY WOODY REGENERATION TO FUEL REDUCTION TREATMENTS IN THE SOUTHERN APPALACHIAN MOUNTAINS

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Abstract—The effects of fuel reduction treatments, fire and mechanical understory removal (alone and in combination), were examined to determine changes in abundance and composition of woody regeneration in the Southern Appalachian Mountains. While mechanical treatment alone (M) had little effect on seedling density, burning (B) and mechanical treatment + burning (MB) produced a significant increase. Sapling density was greatly reduced in MB immediately following treatment, but 2 years later abundant sprouting was observed. Regeneration of shade-tolerant species was encouraged in M and B, whereas MB favored shade-intolerant species. Reponses of dominant tree species varied by treatment based on species' reproductive strategies. Red maple (*Acer rubrum* L.) increased in B primarily through seed germination, whereas MB promoted sprouting. Yellow-poplar (*Liriodendron tulipifera* L.) showed rapid initial response to B and MB, but seedlings that germinated after fire in B did not persist. In contrast, seedlings germinating following treatment in MB thrived, quickly growing into the saplings. B and MB contained more than twice as many oak (*Quercus* spp.) seedlings recorded pretreatment, with the majority sprouting from remaining stems; however, a large acorn crop 1 year after burning contributed to seedling numbers observed the third year posttreatment. Shrub abundance was greatly reduced by M and MB, but sprouting in the understory layer was observed in all treatment units. Reducing fuel using techniques described here can affect woody species composition and potentially change development of mixed-oak forests in the Southern Appalachian Mountains.

INTRODUCTION

The selective use of fire by Native Americans for hunting, land clearing, pest control, and habitat improvement for wildlife (Carroll and others 2002) shaped vegetation composition throughout the Southern Appalachian Mountains (Delcourt and Delcourt 1997). Continued burning and logging by early European settlers promoted species adapted to frequent disturbances (Abrams 1992). However, fire suppression/exclusion practices in the early 1900s influenced stand structure and vegetation composition as late-successional, fire-intolerant species began to establish in these forests (Abrams and Nowacki 1992, Schuler and Gillespie 2000). At the same time, mountain laurel (*Kalmia latifolia* L.) and rhododendron (*Rhododendron* spp.) proliferated forming a dense shrub layer, subsequently affecting seedling recruitment (Waterman and others 1995) and increasing wildfire risk. To mediate these changes, prescribed burning and mechanical removal of fuel have been suggested to reduce fuel loading and encourage re-establishment of vegetation characteristic of forests that developed under frequent fire occurrence.

We examined changes in woody species composition following fuel reduction treatments in mixed-oak stands in the Southern Appalachian Mountains. Regeneration of dominant tree species and ericaceous shrubs was analyzed to identify shifts in species composition that may influence future development of mixed-oak forests in this region. Our work is part of a larger, multidisciplinary research project initiated to reduce fuels and help restore vegetation in forests across the United States that historically were sustained by frequent, low-intensity fires. By re-introducing fire and using other fuel reduction methods, researchers are studying the challenges of reducing fuels while restoring stand structure and ecosystem processes.

METHODS

The study is on the 5,800-ha Green River Game Land east of Hendersonville, NC. Stands are representative of second-growth mixed-oak forests in the Southern Appalachian Mountains with a dense ericaceous shrub layer. Oaks (*Quercus* spp.) represent 55 to 70 percent of overstory basal area; but other hardwoods, such as sourwood (*Oxydendrum arboreum* (L) DC.), red maple (*Acer rubrum* L.), yellow-poplar (*Liriodendron tulipifera* L.), mockernut hickory (*Carya alba* (L.) Nutt. ex Ell.), and blackgum (*Nyssa sylvatica* Marsh.), also are common. Topography is highly dissected with elevations ranging from 366 to 793 m and slopes up to 84 percent. Soils are primarily mesic Typic Hapludults (Evard and Cliffield Series) with inclusions of mesic Typic Dystrudepts (Edneyville and Chestnut Series) (Keenan 1998). These soils are described as deep and well drained in mountain uplands. Small areas of mesic Fluvaquentic Dystrudepts (Arkaqua Series) and mesic aquic Hapludults (Dillard Series) are also present (Keenan 1998).

Four experimental units of at least 14 ha were established at three locations (blocks) for treatment application. Blocks were selected based on size (large enough to include four treatment units), forest age (80 to 120 years), cover type (mixed-oak forest), and management history (had not been thinned in at least 10 years or burned within 5 years). Within each block, one of four treatments (untreated control (C), mechanical-only treatment (M), burn-only treatment (B), or mechanical treatment + prescribed burning (MB)) was randomly assigned to experimental units. Pretreatment sampling occurred from May through August 2001. The mechanical treatment was installed in winter 2001-2002 using contract chainsaw crews who cut all sapling trees >1.4 m tall and <10 cm d.b.h., as well as all ericaceous shrubs. Cut material was left in place onsite. Burning was conducted 1 year after mechanical treatment (March 2003) to allow slash

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to cure. Our burn objectives were to topkill suppressed trees and reduce shrub cover using low- to medium-intensity fires. Ambient temperatures during burning were 17 to 27 °C, the minimum RH was 30 percent, and SW winds were light (3 to 5 km per hour). Fire intensity in MB was consistently greater than B, as mean maximum temperatures exceeded 370 °C as opposed to 180 °C for B.

Ten 0.1-ha plots (20 by 50 m) were randomly located within treatment units using a permanently marked, geo-referenced 50-m grid. Five subplots (10 by 10 m) within each 0.1-ha plot were used to record sapling density (trees >1.4 m tall and <10 cm d.b.h.) and to visually estimate cover of shrubs >1.4 m tall. Woody vegetation <1.4 m tall was measured in 1-m^2 quadrats located in opposing corners of each 10- by 10-m subplot (n=20 per 0.1 ha-plot). We tallied tree seedlings by species and noted origin status (germinant, established, sprout). We recorded ocular estimates of abundance for all woody species using cover classes: <1, 1 to 10, 11 to 25, 26 to 50, 51 to 75, >75 percent. All plants were identified to species level following USDA PLANTS database nomenclature (USDA, NRCS 2006). "Seedling" and "sapling" are used to refer to all stems within each respective category (i.e., "seedling" includes new germinants, established individuals, and sprouts) except where specified.

To analyze treatment effects on woody vegetation, we performed repeated measures ANOVA on sapling and seedling stem densities and shrub cover. Stem densities were summed across treatment unit and square-root transformed to improve normality. Cover class data were assigned the median value for each class, averaged across the treatment unit, and arcsine square-root transformed. Treatment and treatment x year interactions at $\alpha = 0.05$ were interpreted as significant effects from treatment and subjected to post-hoc comparisons using Tukey's multiple comparison procedure.

RESULTS

Fuel reduction treatments significantly affected seedling (P_{trt} <0.0001; P_{year} <0.0001; $P_{trtXyear}$ = 0.0001) and sapling (P_{trt} = 0.0004; P_{year} <0.0001; $P_{trtXyear}$ = 0.0016) density. Immediately following treatment, B and MB contained more seedlings than C and M, a trend which continued through the third-year sampling (fig. 1a). Sapling layer stem density was significantly reduced by all treatments after the first growing season. By year 3, M and B had yet to return to pretreatment levels, whereas MB contained three times more saplings per hectare than prior to treatment (fig. 1b).

Species composition changed dramatically as pretreatment shade-tolerant species, comprising 38 percent of the seedling layer and 68 percent of the sapling layer, increased seedling density in M from 6,367 to 13,967 stems/ha; in B from 15,517 to 78,583 stems per hectare; and in MB from 9,767 to 36,283 stems per hectare. Density of shade-tolerant saplings was little changed from pretreatment values in B (1,077 stems per hectare), whereas M declined from 933 to 740 stems per hectare and MB increased from 1,096 to 2,242 stems per hectare. Even though overall stem density for shade-tolerant species increased in MB, relative density dropped by 15 percent. For shade-intolerant species, treatments increased seedling density for all units (M: 7,067 to 11,400 stems per hectare; B: 6,600 to 26,833 stems per hectare; and MB: 7,117 to 33,650 stems per hectare); but only MB showed notable increases in relative density (+13 percent). Burning (B and MB) resulted in more shade-intolerant saplings (B increased from 146 to 236 stems per hectare; MB increased from 225 to 1,314 stems per hectare), whereas M reduced shade-intolerant sapling density from 240 to 142 stems per hectare.

Regeneration of dominant tree species differed among treatments based on reproductive strategies. Red maple showed significant effects from treatment as B encouraged seedling germination and MB promoted sprouting (fig. 2a,b). Although immediately following treatment, maple seedling density remained relatively unchanged from pretreatment values. After 3 years, B had more seedlings/ha than all other treatments, with new germinants comprising 83 percent of maple stems present. Following initial declines in maple sapling density, M and B showed few differences in number of stems per hectare from pretreatment levels, whereas sapling density doubled in MB. Medium-intensity burns in MB caused more maple overstory mortality (table 1), resulting in vigorous stump sprouting.

Burning (B and MB) elicited an immediate increase in yellow-poplar seedling density from < 450 to > 30,000 stems per hectare with new germinants accounting for 90 percent of stems in both treatments (fig. 2c). However, in B, the third-year inventory revealed 76 percent mortality of these stems. In contrast, seedlings in MB flourished and quickly grew into the sapling category, greatly increasing stem density (fig. 2d).

Oak seedlings responded positively to burning (B and MB), doubling in density over 3 years, whereas oak seedling density in unburned units (C and M) declined (fig. 2e). In the first growing season after treatment, sprouts comprised > 87 percent of oak seedlings for both B and MB. By the third posttreatment sampling, 50 percent of oak seedlings were new germinants. In the sapling layer, only MB had a positive effect on oak-regeneration density (fig. 2f). Both M and B resulted in declines in oak sapling density, which was unexpected, given oak's ability to sprout in response to disturbance.

Although shrub cover < 1.4 m tall showed no significant treatment effects (P = 0.1430), there was a treatment x year interaction (P = 0.0425). The first posttreatment sampling indicated shrub cover was reduced by all treatments; however, 2 years later abundance had recovered (table 2). Tall shrubs showed significant declines (P_{trt} = 0.0442; Pyear = 0.0071; $P_{trtXyear}$ = 0.0293) with large reductions in cover from mechanical treatment (M and MB). Mountain laurel and rhododendron dominated the shrub layer contributing the

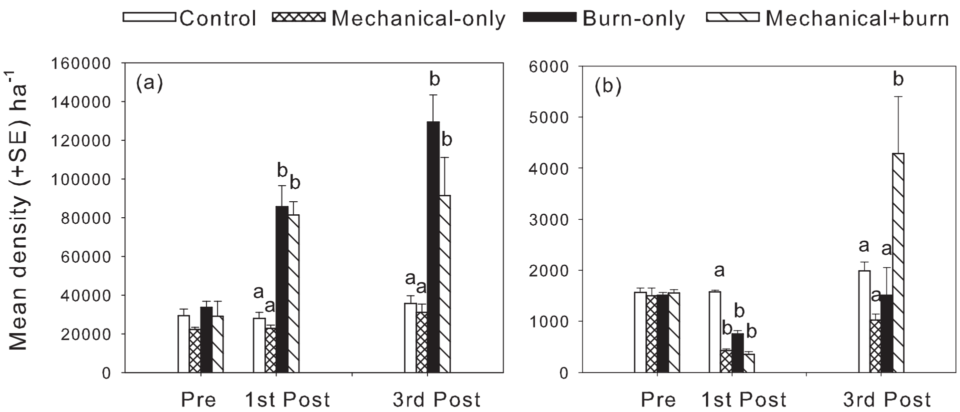

Figure 1—Mean density (+SE) for tree seedlings (a) and saplings (b) in mixed-oak stands treated for fuel reduction.

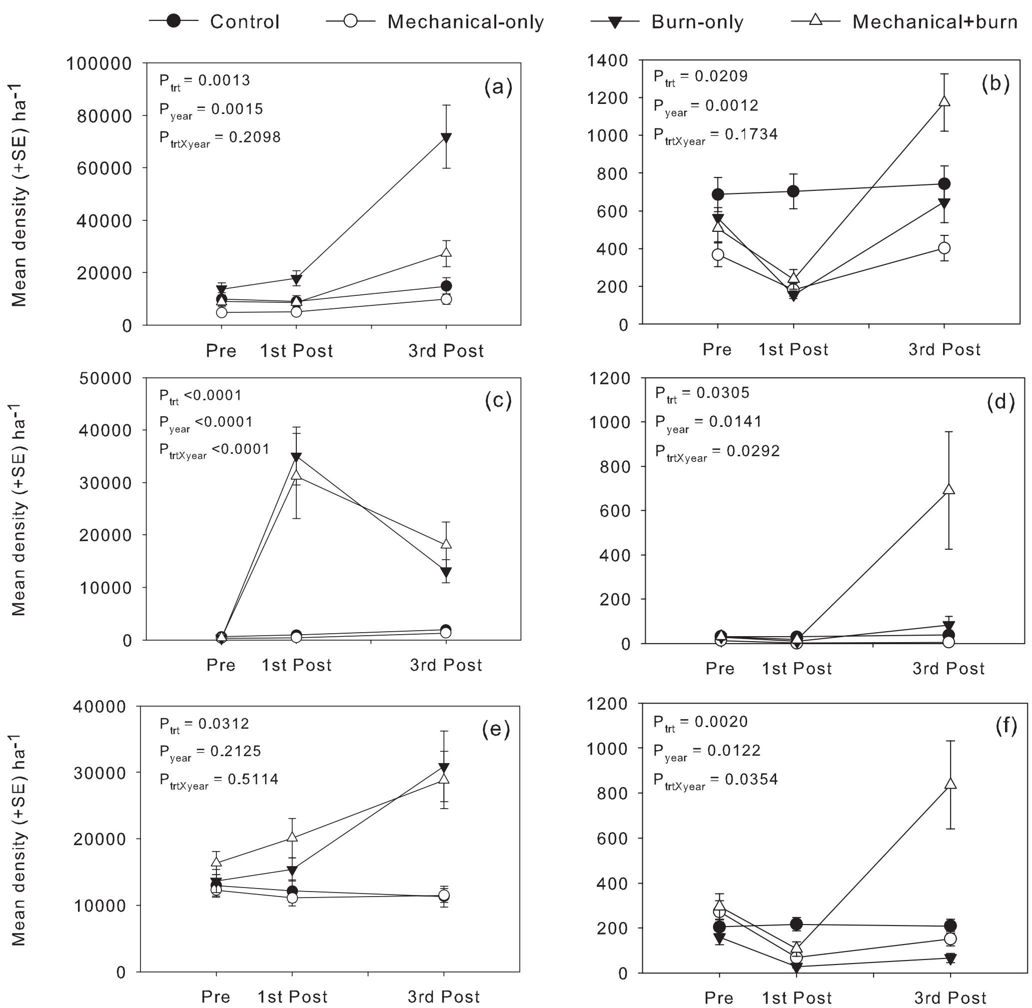

Figure 2—Changes in seedling (a, c, and e) and sapling (b, d, and f) densities for common tree species: red maple (a and b); yellow-poplar (c and d); and oak species (e and f).

Table 1—Overstory abundance of oak, red maple, and yellow-poplar in mixed-oak forests subjected to fuel reduction treatments on the Green River Game Lands in southwestern North Carolina

		Basal Area (m^2/ha)				Density (stems/ha)			
		Oak	Red Maple	Yellow-poplar	Total	Oak	Red Maple	Yellow-poplar	Total
Control	Pre	17.9	1.7	1.7	27.4	269	61	28	566
	1st Yr Post	18.0	1.6	1.7	27.0	261	55	26	551
	3rd Yr Post	18.5	1.8	1.8	28.1	265	57	26	560
Mechanical-only	Pre	19.1	1.0	1.1	27.4	324	55	18	603
	1st Yr Post	19.3	1.0	1.2	27.7	319	53	18	591
	3rd Yr Post	20.0	1.0	1.2	28.8	315	53	17	595
Burn-only	Pre	15.2	2.5	2.1	27.1	208	79	30	569
	1st Yr Post	15.1	2.4	2.1	26.4	199	76	29	541
	3rd Yr Post	15.1	2.3	2.2	26.2	184	71	27	508
Mechanical+burn	Pre	16.6	2.0	1.0	23.9	239	69	13	507
	1st Yr Post	14.7	1.7	1.0	21.0	177	44	11	380
	3rd Yr Post	12.9	1.5	1.0	18.3	141	30	9	277

Table 2—Changes in percent cover of ericaceous shrubs >1.4 m in height (tall shrubs) and understory woody stems <1.4-m tall (excluding tree seedlings) resulting from fuel reduction treatments.

	Control			Mechanical-only			Burn-only			Mechanical+burn		
	Pre	1st Yr Post	3rd Yr Post	Pre	1st Yr Post	3rd Yr Post	Pre	1st Yr Post	3rd Yr Post	Pre	1st Yr Post	3rd Yr Post
Tall Shrubs (>1.4m)												
Mt. laurel	9.7	10.4	11.4	5.3	0.4	1.0	1.9	0.8	0.5	6.2	0.0	0.0
Rhodo spp	2.4	4.3	2.9	7.9	0.4	0.6	4.7	3.5	3.4	1.3	0.0	0.0
Blueberry	0.7	2.1	3.4	0.9	0.4	0.7	0.3	0.0	0.0	1.0	0.0	0.1
Total	13.9	17.8	19.9	14.8	1.3	2.5	7.3	4.6	4.1	9.3	0.2	1.2
Woody Understory Stems(<1.4m)												
Mt. laurel	4.7	3.4	3.1	6.3	4.1	5.1	3.5	0.9	2.3	5.8	1.3	5.4
Rhodo spp	0.1	0.2	0.2	0.7	0.7	1.0	0.2	0.1	0.2	0.0	0.0	0.1
Blueberry	6.8	6.5	3.2	8.2	8.2	7.7	5.3	2.1	4.4	10.8	4.3	10.8
Total	12.6	11.3	7.2	16.2	14.7	15.6	10.3	3.8	8.6	18.2	6.6	18.9

The category "Rhodo spp." includes both *Rhododendron maximum* and *R. minus*.
"Total" is the mean cover for all shrubs species recorded within each treatment.

majority of cover in tall shrubs and blueberry (*Vaccinium* spp. L.) providing the greatest cover for shrubs < 1.4 m tall.

DISCUSSION

Fuel reduction treatments changed patterns of tree recruitment in these mixed-oak stands. Significantly more seedlings were present in burned areas; however, B favored shade-tolerant species, whereas MB caused overstory mortality, creating large canopy gaps and encouraging regeneration of shade-intolerant species. The increase in shade-tolerant species following the B treatment contradicts findings by Dolan and Parker (2004) and Hutchinson and others (2005). Greater stem densities of red maple in B largely contributed to the trend of increasing shade-tolerant species. Low-intensity fires produced patchy burn coverage and had little effect on overstory trees. This effect, coupled with the higher abundance of maple in B provided an ample seed source for tree regeneration in this treatment.

The combination of mechanical understory removal + prescribed burning promoted yellow-poplar and oak regeneration as seedlings (new germinants and sprouts) flourished and quickly grew into the sapling layer. While these species' responses were similar, their reproductive strategies differed. Yellow-poplar was uncommon in the understory prior to treatment probably because of the lack of large disturbances (Busing 1995) in these stands as they have not experienced fire or thinning in over 50 years. Burning removed leaf litter, improving habitat for seed germination and the proliferation of new seedlings (Beck 1965). The fires in MB caused sufficient overstory mortality, providing enough light to allow yellow-poplar seedlings to quickly increase in height. Although yellow-poplar regeneration was also abundant in B the first-growing season after treatment, sufficient light was not available to sustain growth similar to that observed in MB.

Significant increases in oak regeneration following application of mechanical + burn treatments primarily resulted from sprouting; however, 50 percent of oaks recorded in year three were new germinant seedlings. A 2004 mast survey by the North Carolina Wildlife Resources Commission found white oak subgenus (e.g., *Q. alba, Q. prinus*, etc.) mast was at the highest level recorded since surveys began in 1983 (Jones 2005). This large crop of acorns may have contributed to the large seedling increase observed between the first- and third-year posttreatment.

The M treatment had little effect on tree regeneration, although it did reduce total sapling density. Coverage and height of mountain laurel and rhododendron, which can reduce seedling densities through competition for resources (Clinton and others 1994), was reduced in this treatment. However, we observed little difference between units with an intact ericaceous shrub layer (C) and those in which the layer was removed (M). This may be because light levels at the forest floor were not substantially increased in M where the forest canopy remained intact, despite the reduced shrub cover. Additionally, competition with tree seedlings remained high, as shrubs < 1.4 m tall returned to pretreatment levels after 3 years.

Burning and mechanical understory removal are potential options for reducing fire hazard and managing succession in these forests, but other ecosystem components must be considered. Changes in herbaceous vegetation could affect species diversity and richness. Results presented here are short-term, and monitoring should continue in order to determine long-term effects on stand development.

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ENERGY CONTENT IN DRIED LEAF LITTER OF SOME OAKS AND MIXED MESOPHYTIC SPECIES THAT REPLACE OAKS

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Abstract—Mixed-mesophytic hardwood tree species are replacing upland oaks in vast areas of the Eastern United States deciduous forest. Some researchers have suggested that the leaf litter of mixed-mesophytic, oak replacement species renders forests less flammable where forest managers wish to restore a natural fire regime. We performed chemical analyses on dried leaf litter from select oak and oak replacement tree species. The litter of oak replacement species was lower in calorific value and higher in mineral ash content than that of oaks. These results support a feedback theory that the flammability of oak litter favors the perpetuation of oaks over fire-sensitive species. Incorporating this information into fuel and fire behavior models will assist forest managers in planning prescribed burning operations in areas where mixed mesophytic hardwood tree species are replacing oaks.

INTRODUCTION

Prescribed fire is an important silvicultural tool in the management of oak (*Quercus* spp.)-dominated forests in the eastern United States (Brose and Van Lear 1998). However, some researchers have suggested that the replacement of upland oaks by mixed-mesophytic hardwood tree species changes the fire regime in eastern deciduous forests. Specifically, the litter of oak replacement species is suggested to be less flammable than that of oaks (Abrams 2005), although differences in leaf litter quality among eastern deciduous tree species have not been documented. The objective of this study was to determine if there were differences in chemical properties of the litter of select oaks and oak replacement species.

METHODS

Leaf Litter Collection and Sample Preparation

We collected freshly fallen leaf litter of three oaks and two species suggested to replace oaks in two to three different stands in the Clemson University Experimental Forest, Clemson, SC. Oak tree species included scarlet oak (*Q. coccinea* Muenchh.), southern red oak (*Q. falcata* Michx.), and post oak (*Q. stellata* Wangenh.). Oak replacement tree species included red maple (*Acer rubrum* L.) and American beech (*Fagus grandifolia* Ehrh.). Dried leaf litter was milled to 60-mesh in a Wiley mill and pressed into 0.5 g pellets for calorimetry and remained in powder form for mineral ash content analysis.

Calorimetry and Mineral Ash Content Analysis

Fuel chemistry is concerned with the total amount of chemical energy in a fuel and its availability to the combustion process (Mutch 1970). Calorific value is a measure of the thermal energy released when a fuel is burned (Dickinson and Kirkpatrick 1985) and was measured using an IKA® C200 oxygen bomb calorimeter using four subsamples per litter species per stand. Mineral ash content affects combustible fuel mass, gas evolution, and ignitability (Broido and Nelson 1964) and was measured as the percent of dry mass remaining after complete combustion of three subsamples per litter species per stand in a muffle furnace (at 600 °C for 2 hours). Calorific values and mineral ash contents of the litter of the oak species and oak replacement tree species were averaged and compared using one-way analysis of variance.

RESULTS AND DISCUSSION

The calorific value of the leaf litter of oak replacement tree species (17,977 ± 248.49 J g^{-1}) was less than that of oak litter (18,676 ± 242.95 J g^{-1}) ($P = 0.0322$). Further, the mineral ash content of the leaf litter of oak replacement tree species (7.27 ± 0.74 percent) was greater than that of oak litter (3.93 ± 0.73 percent) ($P = 0.0028$).

The results of this study suggest sites dominated by mixed-mesophytic hardwood tree species may exhibit lower fire intensities than those dominated by oaks because calorific value greatly influences heat output (Dickinson and Kirkpatrick 1985). Additionally, sites dominated by mixed-mesophytic species may be less flammable and/or burn more heterogeneously than those dominated by oaks because increasing mineral ash content decreases ignitability (Broido and Nelson 1964).

CONCLUSION

In our study, the leaf litter of oak replacement tree species had lower calorific value and higher mineral ash content than that of oak species. These results support a feedback theory that the flammability of oak fuel complexes favors the perpetuation of oaks over mixed-mesophytic, fire-sensitive tree species. Oak replacement might be expected to make it increasingly difficult to accomplish silvicultural objectives with prescribed fire. However, incorporating information regarding fuel quality into fuel and fire behavior models should assist forest managers in modeling and manipulating prescribed fire in areas where mixed-mesophytic hardwood tree species are replacing oaks.

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SPACING AND FAMILY AFFECT FUSIFORM RUST INCIDENCE IN LOBLOLLY PINE AT AGE 17

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Abstract—The effects of fuel reduction treatments, fire and mechanical understory removal (alone and in combination), were examined to determine changes in abundance and composition of woody regeneration in the Southern Appalachian Mountains. While mechanical treatment alone (M) had little effect on seedling density, burning (B) and mechanical treatment + burning (MB) produced a significant increase. Sapling density was greatly reduced in MB immediately following treatment, but 2 years later abundant sprouting was observed. Regeneration of shade-tolerant species was encouraged in M and B, whereas MB favored shade-intolerant species. Reponses of dominant tree species varied by treatment based on species' reproductive strategies. Red maple increased in B primarily through seed germination, whereas MB promoted sprouting. Yellow-poplar (*Liriodendron tulipifera* L.) showed rapid initial response to B and MB, but seedlings that germinated after fire in B did not persist. In contrast, seedlings germinating following treatment in MB thrived, quickly growing into the saplings. B and MB contained more than twice as many oak (*Quercus* spp.) seedlings recorded pretreatment, with the majority sprouting from remaining stems; however, a large acorn crop 1 year after burning contributed to seedling numbers observed the third year posttreatment. Shrub abundance was greatly reduced by M and MB, but sprouting in the understory layer was observed in all treatment units. Reducing fuel using techniques described here can affect woody species composition and potentially change development of mixed-oak forests in the Southern Appalachian Mountains.

INTRODUCTION

Fusiform rust disease is caused by the fungi *Cronartium quercum* (Berk) Miyabe ex Shirai f. sp. fusiforme. This disease affects loblolly pine (*Pinus taeda* L.) as well as slash pine (*P. elliottii* Englm.). Due to the detrimental effects this disease can have on these species, genetic improvement has been extensively studied in which family performance, geographic location effects, and interactions have been considered.

Genotype-by environmental interactions have been considered negligible in several studies (Hodge and others 1993, Kinloch and Stonecypher 1969, McKeand and Amerson 1999). On the other hand, others have shown that various families have differing responses to rust inoculums from various regions (Power and others 1977, Snow and others 1975), and thus interaction effects should be considered. Also, current molecular approaches have led to the identification of a few major genes which control resistance (Kubisiak and others 2004, Wilcox and others 1996). The possibility of the few resistance genes being overcome by a variant of the fungus from a different location has led to general recommendations of deploying several half-sib families in either pure or mixed family deployment (Bridgewater and others 2005, McKeand and others 2003).

A loblolly pine stand 17-years old is approaching, if it has not already reached, stand volume allowing a merchantable harvest. This study investigates virulence presence in living 17-year stems in half-sib loblolly pine families. Family and environmental effects are studied. However, environmental effects in this study are effects of scale (i.e., spacing). Better control of infection may be possible through use of spacings that allow the trees to maintain greater vigor. Furthermore, deployment effects will be analyzed to determine if decreased infection can be achieved through deployment of mixed families or single pure family plots.

METHODS

Plant Material and Experimental Design

Containerized seedlings of eight open-pollinated families in North Carolina (NC) and one open-pollinated "genetic check" (bulk seed lot) from east-central Mississippi (MS) and west-central Alabama (AL) were provided by Weyerhaeuser Company. Seedlings were planted during April 22 to May 7, 1985 at two sites on the John Starr Memorial Forest (Mississippi State University school forest) in Winston County located in east-central MS. The experimental design was a randomized complete block with four replications at each site. The two sites were an old field and a cutover site-prepared area. Treatments were arranged in split-split plots, where each rep was split into three spacings (5 by 5, 8 by 8, 10 by 10 feet). Each spacing was split into a mixed family subplot and a pure family subplot. The pure family subplot contained nine sub-subplots, each having one family or check. A single or double border row was planted around each sub-subplot. The interior trees of each pure family sub-subplot covered an equal area of 0.0367 acres so that there were 64, 25, 16 trees in each plot of the 5 by 5, 8 by 8, 10 by 10 feet spacings, respectively. The mixed family subplot did not contain the check and covered an area equal to the eight sub-subplots in the pure family subplot. In this mixed deployment, families were randomly planted while maintaining equal representation of each family. Survival, d.b.h., and total height were recorded at ages 5, 9, 13, and 17 and presence of stem fusiform rust galls were recorded at age 17.

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ANALYSIS

Presence or absence of fusiform rust galls per stem is a binary trait (0 or 1) and cannot be analyzed traditionally because it violates the assumption of residual normality and homogeneity in general linear modeling (GLM). Thus, this analysis used stems infected at age 17 divided by live stems at age 17 (percent infection) in each plot as the response variable. Use of this measurement in conjunction with the large sample size satisfies the assumptions and allows infection to be gauged on a stand level. Analysis of family and spacing differences was conducted only using pure family plots and the mixed model used was:

$$y_{j(i)l} = \mu + \tau_i + \beta_{j(i)} + \alpha_k + \phi_l + (\tau\alpha)_{ik} + (\tau\phi)_{il} + (\beta\alpha)_{j(i)k} + (\beta\phi)_{j(i)l} + (\alpha\phi)_{kl} + (\tau\alpha\phi)_{ikl} + (\beta\alpha\phi)_{j(i)kl} \begin{cases} i = 1,2 \\ j = 1,2,3,4 \\ l = 1,2,\ldots,9 \end{cases} \quad (1)$$

where y was the percent infection, μ was the overall population mean, τi was the effect of the ith site, βj(i) was the effect of the jth replication nested in the ith site, αk was the fixed effect of the kth spacing, and was the random effect of the lth family. Duncan's New Multiple Range Test was used to test for differences among individual families. Correlations between family means for growth traits (i.e., height, d.b.h., stem volume, and stand volume) and family infection percentages were calculated using Pearson's Correlation Coefficient. Analysis of deployment used the simpler fixed effects model:

$$y = \mu + \alpha_i + \beta_{j(i)} + \tau_k + \alpha\tau_{ik} + \beta\tau_{j(i)k} + \lambda_l + \alpha\lambda_{il} + \beta\lambda_{j(i)l} + \delta_m + \alpha\delta_{im} + \beta\delta_{jm} + \alpha\beta\delta_{ijm} + \tau\delta_{km} + \alpha\tau\delta_{ikm} + \beta\tau\delta_{j(i)km} + \lambda\delta_{lm} + e \begin{cases} i = 1,2 \\ j = 1,2,3,4 \\ k = 1,2,3 \\ l = 1,2 \\ m = 1,2,\ldots,8 \end{cases} \quad (2)$$

where y was percent infection, μ was the overall population mean, α was the effect of the ith site, β was the effect of the jth replication nested within the ith, τk was the kth spacing, λl was the effect of the lth deployment, and δm was the effect of the mth family. Three-way and four-way interactions between deployment-by-family and site, replication, and spacing were not significant and were subsequently pooled into the sub-subplot error term.

RESULTS AND DISCUSSION

Family and Spacing Effects

Average stand infection percentage per plot was 14.9 percent (s.d.= 0.05). A significant difference (p-value<0.0001) existed between the two sites where the old field had 18.3 percent infection and the cutover, site-prepared area had 11.5 percent infection. Both family and spacing independently affected the percent infection at the alpha=0.05 level (p-values= 0.0032 and 0.0087 respectively). Range among families was substantial, with a low of 8.4 percent for family NC8 and a high of 27.3 percent for family NC3 (table 1). Families such as NC2 and NC3 and the Check have been shown in previous studies (Adams and others 2006, Land and others 2004) to be relatively marginal in regards to stand volume and average height. In this study, these families show a greater infection percentage further decreasing their value. Interestingly, greater individual stem growth rates have generally been associated with greater infection incidences (Burton and others 1985, Eaton and others 2006, McNab and others 1990, Schmidt 1998). This has been attributed to rapid growth, in which new, rapidly dividing cells are more susceptible to fungal infection. On a tree level, this study supports this. Stems that produce large individual tree volumes (e.g., families NC2 and NC3 (Adams and others 2006)) had greater infection prevalence. However, on a stand level the fastest growth, greatest volume producing families had significantly lower infection percentages. Families NC4, NC7, NC1, and NC8 were all statistically the same in regards to infection percentage and comprised four of the top five stand volume producing families (Adams and others 2006).

Table 1—Duncan's test of ranked family and spacing infection percent means at age 17 for pure family deployment

Family	Mean[a] (%)	Grouping[b]
NC3	26.3	A
Check	21.7	AB
NC2	20.9	AB
NC6	17.6	B
NC5	16.7	B
NC4	10.6	C
NC7	10.5	C
NC1	10.3	C
NC8	8.4	C

Spacing (feet)	Mean[a] (%)	Grouping[b]
10x10	17.6	Y
8x8	15.7	YZ
5x5	13.7	Z

[a] Mean infection percent calculated from (# live trees infected at age 17)/(# live trees at age 17).

[b] Means followed by the same letter and case are not significantly different at the 0.05 probability level.

Spacing effect does seem to support the supposition that rapidly growing trees are more susceptible to infection. The 10 by 10-foot spacing, which provides the greatest potential for rapid tree growth, had the highest infection percentage (table 1). Percent infection decreased as the spacing size decreased from 8x8-foot to 5 by 5-foot spacing. Though this effect was significant, the difference between the 10 by 10-foot and the 5 by 5-foot spacing was only 3.9-percent. However, closer spacing may have less prevalence simply because infected trees have died prior to age 17.

Correlations between age 17 infection percentage and growth traits generally became significant with age. At age 13, height and stand volume were negatively correlated with infection (table 2). On the other hand, diameter growth was positively correlated with increases in infection percentage. Correlation with diameter became significant at the early age of five and remained strong through age 17. Tree volume was only significant at age five but was not strongly correlated after that. This is probably due to the inverse correlations that diameter and height, both used for calculation of stem volume, had with percent infection. The reverse correlations exhibited by diameter and height with infection percentage seem to counter one another. However, once survival is taken into account in calculating stand volume, the more vigorous trees at the stand level had fewer rust incidences. In this study, families with the largest diameters achieved this at the expense of surviving stems. Thus these families were, relatively sensitive to competition and had more prevalence of rust among surviving stems at age 17 while less competition-sensitive families produced greater stand volume and had fewer incidences.

Mix-family Versus Pure-family Deployment

Analysis with consideration for deployment types (i.e., mixed-family deployment and pure-family deployment) showed that there was significant interaction (p-value=0.05) between deployment type and family for rust infection. Most interaction (change in rank) was associated with the change in family NC1. Families NC2 and NC3, which had the highest infection percentages in the previous analyses of pure family deployment, had infection percentages significantly lower when deployed in a family mixture (fig. 1). Families NC5 and NC6, which also had high infection percentages in pure-family blocks, had decreased infection, though not significant, in the mixed deployment. Families with fewer rust incidences in pure-family subplots (e.g., NC1 and NC8) had slightly more, though not significant, infection in the mixed-deployment.

On the subplot level (i.e., mixed- versus pure-family deployment subplots), rust infection percentage at the a priori 0.05 alpha level was not significantly different by deployment. However, a p-value of 0.10 makes this factor at least highly influential with average infection percentage 14.27 percent and 15.16 percent for the mixed- and pure-family deployment subplots respectively. This lends support for the use of mixed-family deployment, not just as an added genetic safeguard, but as a direct way to minimize stand

Table 2—Pearson's Correlations Coefficients between infection percentage[a] at age 17 and growth traits for pure family deployment

Growth Trait	Age-5	Age-9	Age-13	Age-17
Height	0.06	-0.13	-0.24**	-0.15*
Diameter	0.23*	0.15*	0.12*	0.15*
Tree Volume	0.21*	0.11	0.08	0.11
Stand Volume	0.00	-0.13	-0.29**	-0.28**

* =Coefficient is significant at the 0.05 level.

** =Coefficient is significant at the 0.01 level.

[a] Mean infection percent calculated from (# live trees infected at age 17)/(# live trees at age 17).

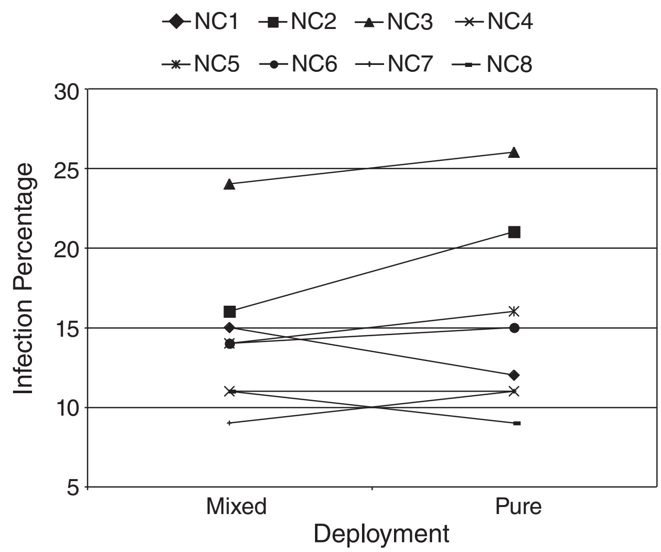

Figure 1—Infection percentage change across deployment in a 17-year old pine stand.

rust prevalence at age 17. Conversely, an argument could be made that less prevalence at age 17 is a function of more rust associated mortality (RAM) through the life of the mixed stand. However, overall survival across spacings and families in both deployments was 59 percent, and does not support the possibility of increased RAM.

The actual cause of the rust prevalence difference by deployment is not clear and two possible factors could be the cause. First, spatial influences could be at work in which more resistant families act as buffers for less resistant trees. A second theory is that rust infection in this study is related to the domination or suppression of various families. The fastest growing (stand volume) families in this study did not exhibit increased infection often correlated with faster growth. These are also the families that exhibited dominant ideotypes (Adams and Land 2006). This domination caused the suppression and decreased growth rates of the more susceptible families. The lack of rapid growth in susceptible families may afford some protection from infection. Still, alternative combinations of families are needed before one or both of these causes can be accepted. Alternative combinations are also needed to test if a difference would exist at all if mixed-family deployment included families that all had greater rust resistance.

CONCLUSIONS

Loblolly pine genetic improvement for stand growth does not preclude breeding toward fusiform resistance. Families with high individual-tree growth rates were associated with greater infection rates, while faster growing families on a stand level in this study did not suffer from increased prevalence of rust at age 17. Decreased density due to spacing did result in more infection among those trees living at age 17. Thus, selection of phenotypes based on individual-tree traits may be adverse for rust resistant selections and losses in quality must be weighed against gain in volume when using wider spacing. While significant, the relatively small decrease in infection using a denser spacing does not warrant alteration of spacing strategies when, alternatively, emphasis can be placed on deployment of fast-growing, resistant genotypes in conjunction with continued promotion of fast growth with silvicultural practices.

Deployment of several families has generally been recommended to ensure adequate genetic diversity so that resistance in not overcome by the fungi. This study supports use of multiple families and highlights that mixed family deployment, in lieu of planting several families in blocks, is directly beneficial for the decrease of rust incidences at age 17. Still, mechanisms that are causing superiority of the mixed deployment are unknown. Spatial relationships among the trees or stand domination/suppression dynamics may be at work.

Impact of family, spacing, and deployment on rust prevalence by this analysis reflect the effect on living stems at age 17. This represents a time at which a stand could have a merchantable harvest. However, variations of both RAM and density related mortality among these factors early in stand history may be masking variation effects. Families or spacings with high early mortality may cause age 17 infection percentages to be lower than the actual susceptibility rate for that treatment. Further studies across stand history will be needed to investigate how age/mortality impacts the final outcome which is presented here.

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ASSESSMENT OF LOBLOLLY PINE DECLINE AND SITE CONDITIONS ON FORT BENNING MILITARY RESERVATION, GA

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Abstract—A decline of loblolly pine (*Pinus taeda* L.), characterized by expanding areas of declining and dead trees, has become prevalent at Fort Benning, GA. A 3-year study was conducted to determine the kinds of fungi, insects, and site disturbances associated with this problem. The insects *Dendroctonus terebrans*, *Hylastes salebrosus*, *H. tenuis*, *Pachylobius picivorus* and *Hylobius pales* were significantly more abundant in symptomatic than in asymptomatic loblolly pine plots. These root and lower stem-infesting insects consistently carried the fungi *Leptographium terebrantis*, *L. procerum*, and *L. serpens*. Root sampling revealed high levels of root damage and mortality, staining and infection with *Leptographium* species. This belowground damage and mortality preceded the expression of aboveground symptoms, such as short chlorotic needles, sparse crowns, and reduced radial growth. A sequence of interactions among this complex of organisms and abiotic factors is proposed as the cause of 'loblolly pine decline.' This study confirms the findings for loblolly pine decline at other geographic locations and validates the Loblolly Pine Decline Risk Map.

INTRODUCTION

Loblolly pine decline is a syndrome associated with loblolly pine (*Pinus taeda* L.) in the Southeastern United States that is reported to occur from eastern MS to central AL, and GA to SC and NC. This decline is similar in symptomology to other pine diseases, such as littleleaf disease of shortleaf pine (*P. echinata* P Mill.) (Campbell and Copeland 1954), and has approximately the same geographic range. The cause of littleleaf disease is usually attributed to a combination of soils that have poor drainage and to the presence of *Phytophthora cinnamomi* Rands (Campbell and Copeland 1954, Oak and Tainter 1988, Roth 1954). Loblolly pine decline complex is characterized by lateral root deterioration prior to crown symptoms, loss of fine roots before mortality, and heavy cone crops. The declining crowns occur within the 30 to 50 year age class when trees express decline symptoms and die prematurely. There is no evidence of bark beetle activity, foliage disease, or heart rot disease to account for the mortality. Loblolly pine decline occurred on sites with abiotic or biotic stress factors that may cause changes in the host chemical profile. These changes are attractive to root feeding insects that vector the fungal pathogen *Leptographium*. The stress conditions affecting host vigor on these sites favor an increase in root-feeding insect populations and associated vector activity (Eckhardt and others 2007, Otrosina and others 1997). *Leptographium* species are vectored by at least 16 different species of Coleoptera. Although an increase in root-feeding insect activity is necessary for the decline to develop, these insect vectors by themselves, do not account for tree mortality. The increase in root-feeding insects does correspond to increased *Leptographium* colonization in roots and contributes to mortality (Eckhardt and others 2007). The primary predisposing factor for initiation of decline apparently relates to site topography parameters found in association with the presence of decline. Loblolly pine decline is generally associated with well-drained convex site features located on moderate to steep slopes with a southerly aspect, and trees in a state of low vigor. A nondecline site tends to have relatively flat to concave site features with a northerly aspect and is associated with trees in a high state of vigor (Eckhardt 2003).

The spatial patterns of abiotic factors in loblolly pine decline identified by Eckhardt (2003) were used in a Geographical Information System (GIS) to delineate loblolly pine decline at a landscape level. In that study the biological data corresponding with the presence of decline was used to identify abiotic parameters and produce a Loblolly Pine Decline Risk Map (LPDRM). The primary question is whether this mapping technique is applicable in delineating loblolly pine decline in other geographic regions with symptoms of loblolly pine decline? This study addresses this question by using the LPDRM in another geographic area and tests the map efficacy in delineation of the biological parameters corresponding to decline.

MATERIALS AND METHODS

The LPDRM was created for the study area Fort Benning Military Reservation (FBMR) which is located in the midwestern portion of GA's Muscogee and Chattahoochee counties that are mid-state on the eastern AL border. The predominant land base is Upper Coastal Plain with some Piedmont transition zone along the Fall Line. FBMR personnel provided the topographic and geographical data from their geospatial database. Topographic data were derived from the 10m Digital Elevation Model (DEM), which is based on contours obtained from the U.S. Geological Survey (USGS) 7.5 minute (1:24,000) topographic quadrangles. Slope and aspect were derived from multiple DEM coverages of the FBMR area. The shape file coverage for FBMR was used to delineate reservation boundaries, stands, compartments, roads, and streams for the pine decline risk map assessment. All data gathered were georeferenced and projected in Universal Transverse Mercator 83 (UTM83) and thus constitute a geographic database of FBMR, Georgia.

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ArcView 3.2 (ESRI 1996), along with the Spatial Analyst extension (ESRI 1996), was used to combine and analyze the different maps created by a series of ArcView 3.2 functions containing multiple steps that create, merge, and intersect parameters of loblolly pine decline. The resulting product spatially presents the topological parameters in a multicolored polygon map (green = minimal, yellow = low, magenta = moderate, and red = high) to classify the level of loblolly pine decline. The reclassified data from the aspect and slope maps have polygons that contain combinations of unique topological parameters associated to decline and represent the occurrence of some level of loblolly pine decline as described by Eckhardt (2003).

Thirty-six 0.07-ha plots were located using a Global Positioning System (GPS) and established using Forest Health Monitoring (FHM) protocols (Dunn 1999). The location of the plots was determined using LPDRM to designate a site as either symptomatic (decline) or asymptomatic (healthy). There were 15 asymptomatic and 21 symptomatic plots established. The symptom categories were divided into four loblolly pine age/size classes: seedlings/saplings < 10-year age class (< 10.0 cm diameter), pulpwood 10- to 19-year age class [> 10.0 cm but < 29.75 cm d.b.h.], 20- to 40-year age class (>29.75 cm d.b.h.), and greater than 40-year age class (>29.75 cm d.b.h.). Pine decline study plots consisted of a 0.02-ha central permanent plot and three 0.02-ha subplots. The subplots were marked off 120 m from the central plot at bearings of 120, 240, and 360 degrees (Dunn 1999).

At each location, a root health assessment was performed on three dominant or codominant pines nearest to the center plot location. Tree species, diameter at breast height (d.b.h., approximately 137 cm aboveground), age, and 5- and 10-year radial growth increments were recorded from each of the root-sampled trees. Roots were collected from the 36 research plots during the summers (May, June, and July) of 2004 and 2005, with 18 plots sampled the first summer and 18 the second. The two-root excavation method was used in which three dominant/codominant trees nearest to the plot center were selected for sampling (modified from Otrosina and others 1997). Two primary lateral roots extending away from the tree base were excavated with hand tools from the root collar out to the approximate crown drip line for each selected tree. Root depth was also recorded at this time. Roots were visually examined for primary root damage and fine root presence or absence, damage, and/or death before removal from soil. Primary roots were defined as the major lateral roots extending from the base of the tree to the drip line. All secondary and feeder roots were categorized as fine roots. Roots that were shriveled and dried were tallied as dead. Trees with primary roots but no secondary root growth were tallied as having their fine roots absent. Damage caused by insects was determined by direct observation at the time of root sampling on every pine on all center and sub-plots. Infestation and damage caused by *Hylastes salebrosus* Eichoff, *H. tenuis* Eichoff, *Hylobius pales* Herbst., and *Pachylobius picivorus* (Germar) (all Coleoptera: Curculionidae) were estimated by sweeping soil away from the root collar and lateral roots, and looking for entrance/exit holes and pitch formation on the bark. Damage was also assessed in the laboratory by peeling the bark from the roots and looking for the presence of insect galleries. Root wedge samples were cut from primary roots at 16-cm intervals, beginning at 16 cm from the root collar. Also, random samples of 2- to 8-cm fine root samples were collected between primary root sample intervals. All root samples were placed in plastic bags and kept chilled in ice chests for transport to the laboratory. Fungal isolations from sampled roots were conducted as previously described by Eckhardt and others (2007). Logistic regression methods using PROCLOGIST (SAS Institute Inc. 2001) were used to analyze the incidence of staining fungi, root damage type, and root health in symptomatic versus asymptomatic plots.

Soil samples were collected from all root-sampled plots in 2004 and 2005. A soil auger was used to collect soil near the lateral roots of three dominant or codominant loblolly pine trees closest to the plot center using a collection pattern that followed Lewis and others (1987). The soil samples collected near each root were placed in individual plastic bags, kept on ice, transported to the laboratory and stored at 4 °C for no more than 3 days. Fungal isolations from sampled soils were conducted as previously described by Eckhardt and others (2007).

Insect activity on plots was determined using pitfall traps (adapted from Klepzig and others 1991) to capture root-feeding insects on the subplots of 31 center plots (three subplots per plot, 93 total pitfall traps) from March to May for the 2003 and 2004 trap year to allow for the best chance of bracketing the emergence period of most bark beetles (Drooz 1985). Insects were collected on a biweekly basis and transported to the laboratory for identification and isolation of associated fungi as described in Eckhardt and others (2007). Data were analyzed using generalized linear procedure models with repeated measures analysis in Proc GLM (SAS Institute, Inc. 2001). The model was $Y = m + \text{treatment}$, where m is the mean and treatment was the treatment effect. When significant treatment differences were indicated, means were separated by Fisher's Protected LSD test ($P = 0.05$).

Plot measurements taken on all center and subplots included tree species composition (pines and hardwoods), tree d.b.h., basal area (tree count using 10 factor prism 0.04-ha plot) for the loblolly pines, and total trees present (Dunn 1999). Additional measurements of sampled trees included age and growth increment (5 and 10 yr) (Dunn 1999). Other site data collected were aspect of slope, percent slope, elevation, topographic position, land form, and percent slope. These data provided a measure of site conditions, stand density, and influence of external stresses. Crown ratings of live crown ratio (comparison of crown length with total tree height), crown light (a measure of light impacting the crown from all sides and the top exposure), crown position (superstory, overstory, midstory, or understory), crown density (percent of crown outlined with living branches and foliage), crown dieback (the ratio of recent fine twig dieback to total live crown), and foliage transparency (percent sunlight transmitted through the living crown) were recorded for all loblolly pines with d.b.h. 12.7 cm or greater to describe relative tree health (FHM protocols, USDA 2001). Trees with high scores for live crown ratio, density and diameter and low scores for dieback and foliage transparency have increased potential for carbon fixation, nutrient storage and increased potential for survival and reproduction (USDA 2001). Crown evaluations quantitatively assessed current tree conditions and provided an integrated measure of site conditions, stand density and influence of external stresses. Resin sampling for vigor of hundred ninety eight trees were sampled (33/decline/age class) on the south side of each tree by punching a hole approximately 137 cm above ground with a 1.9 cm diameter arch punch (No. 149 Osbourne). A plastic resin sampler (Missoula Technology Development Center, Montana) was screwed in place over the punch hole with two wood screws. A pre-weighed polyethylene terephthalate (PET) Corning® 15 ml centrifuge tube was screwed into the resin sampler and left for 24 hours. Centrifuge tubes with resin were then collected, capped, and put on ice for transport to laboratory. Resin weights were determined. Plot measurements were analyzed using ANOVA. Data collections on study plots involving forestry mensurations, resin sampling, and crown conditions were conducted by Forest Service and University personnel trained and certified in the respective forestry practices and completed on a blind treatment basis (USDA 2001).

RESULTS

Topography

Plots had elevation ranges from 98 to 175 m and a 139 m mean, and aspect ranges from 5° to 360° and a 234° mean, with a slope range from 1 to 12 percent and a 6 percent mean. The assessment of the LPDRM for the 36 plots indicated accurate identification for 13 of 15 (86 percent) asymptomatic and 21 of 21 (100 percent) symptomatic plots. Slope greater than 5 percent was the only topographic factor that was statistically significant ($F_{1, 36}$=10.1, p=0.0031) by treatment. At slope greater than 5 percent, decline incidence increased. No other site topography factors had statistical significance when compared to treatment and when alone, appear to have only minor effects. Although the LPDRM was still highly accurate at identifying sites by symptom category and was used effectively to do so, other biological parameters associated with symptom categories were used to verify this as well (e.g., radial growth, crown condition, resin weight, root condition, and insect activity).

Growth Variables

Tree ages ranged from 6 to 84 years in the study plots. The range of d.b.h. measurements for loblolly trees sampled for growth and vigor was 10.4 to 53.3 cm. Higher mean d.b.h. was to be shown significant in symptomatic trees when correlated to radial growth ($F_{1, 49}$=5.42, p=0.0241) in the 10- to 19-year age category. The 5-year radial growth ranged from 4.5 to 31.4 mm, and 10-year radial growth was 9.8 to 58.45 mm. Asymptomatic plots had trees with increased radial growth in 5- and 10-year measurements. The increased 5- and 10-year radial growth was statistically significant in asymptomatic plots compared to symptomatic for the tree age categories 10 to 19, 20 to 40, and 40+ (table 1). The range of height for trees on the study plots was 16 to 88 feet. There was no significant difference in the mean d.b.h. and tree height measurements when overall means for symptomatic vs. asymptomatic trees were compared by age category. A response trend indicating reduced d.b.h. and tree height means for symptomatic plots began in the 30- to 39-year age category and continued through 40+ years.

Crown Condition

Three crown conditions (crown density, crown ratio, and foliar transparency) were found to be statistically significant when compared to symptom category. The age category for pulpwood (10 to 19) had foliage transparency reported as significant ($F_{1, 437}$ =14.27, p=0.0002) and in age category 20-40 crown ratio ($F_{1, 451}$=9.52, p=0.0002) was significant for symptomatic categories (table 2). This may be a result of crown rating tree locations, as not all crown rated trees were on the center plot where the plot is risk rated.

Resin Analysis

Mean resin weights were 10.8 g for asymptomatic and 6.1 g for symptomatic sampled trees. Resin weights on asymptomatic plots were statistically significant when compared to symptomatic plots and by age 10 to 19 years ($F_{1, 65}$=19.59, p<.0001), 20 to 40 years ($F_{1, 65}$=26.33, p<.0001), and 40+ years ($F_{1, 65}$=23.28, p<0.0001).

Root Condition/Isolations and Soil Isolations

Leptographium species were isolated from the primary and fine root samples from 23 of the 36 plots and from the soil in 5 of the 36 plots. *Leptographium* species isolated from the primary root samples were *L. terebrantis* Barras & Perry, L. *procerum* (Kendr.) Wingfield, *L. serpens* (Goid.) Wingfield, and an unidentified *Ophiostoma* sp. Only *L. procerum* was isolated from the fine roots. The overall proportion of *Leptographium* species isolated was higher from roots of trees on symptomatic plots (91 percent) than those from asymptomatic plots (0.08 percent). In addition, only *L. procerum* was isolated from the soil samples and was generally more common in soil from symptomatic (80 percent) vs. asymptomatic (20 percent) plots. Root system deterioration was significantly higher in symptomatic than in asymptomatic trees. Symptomatic trees consistently had more dead and fewer fine roots present, more physical damage from insects and fire, more staining of the primary roots, and a higher percentage of *Leptographium* species per root system.

Insect Variables

The total number of root-feeding insects (*Hylastes* spp.) and reproduction weevils (*Hylobius pales* and *Pachylobius picivourus*) captured in pitfall traps increased annually during the 3 years of trapping (1117 in 2003, 1253 in 2004 and 2423 in 2005). The mean pest insect abundance for all plots and years increased from 82.78 to 127.33. Mean insect numbers were significantly higher on symptomatic plots than asymptomatic plots for study years 2003 ($F_{1, 30}$=4.22, p=0.0495) and 2004 ($F_{1, 30}$=4.33, p=0.0468) (fig. 1). Mean insect abundance increased when plots had a history of disturbance (burning, thinning, or feral hog rooting) and when multiple disturbances occurred (fig. 2). Insect abundance by age category was statistically significant ($F_{3, 123}$ =10.52, p<0.0001) with higher abundance in precommerical (< 10 years) and 40+ years (fig. 3). Mean insect abundance of different root feeders was similar; symptomatic

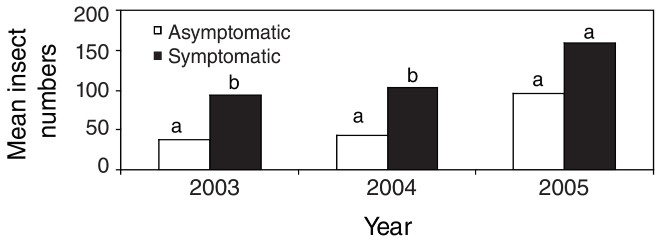

Figure 1—Mean insect abundance by plot treatment for all trap years on Fort Benning Military Reservation. Bars with the same letter at each treatment are not significantly different (P> 0.05).

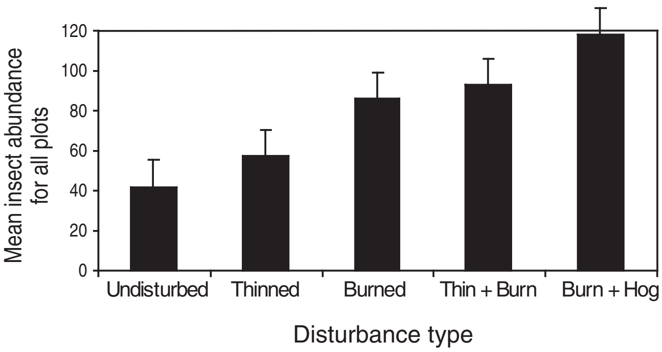

Figure 2—Mean abundance of insects captured at Fort Benning Military Reservation for all plots, all years, and segregated by the type of disturbance on plots.

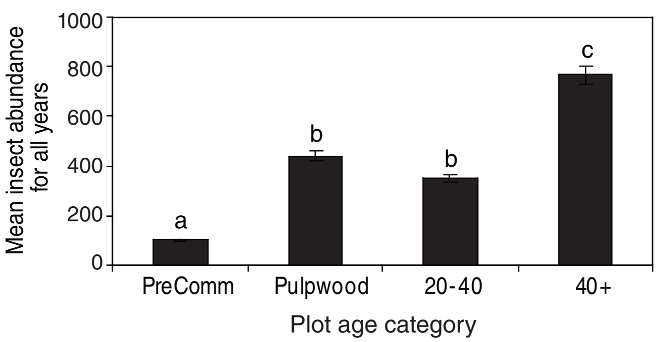

Figure 3—Mean insect abundance per plot for all trapping years (2003 to 2005) segregated by age category (PreComm <10 years, Pulpwood 10 to 19 years) of the plots on Fort Benning Military Reservation. Bars with same letter for each age category are not significantly different (p > 0.05).

plots had greater numbers than asymptomatic plots, and insects were more abundant in older tree age categories.

DISCUSSION

The abiotic factors that predispose trees to decline may be the result of changes in the pine physiology that provides an environment favorable to predisposing biotic factors (Hodge and others 1979). Decline symptoms appeared to be more pronounced in areas that had steeper slopes and a south-facing aspect. These microsite conditions are primarily associated with minor changes in topography that create distinctive environmental conditions and appear to be the essential elements correlating to the biology of decline. Microsite differences are often strongly correlated with whether the site is symptomatic or not, the presence of an association of root-feeding insects and *Leptographium* fungi, and loblolly pine vigor. The topography of microsites was correlated with abiotic conditions (positive or negative) to which loblolly pine responded physiologically with changes in growth parameters, vigor, insect abundance, isolation rates of *Leptographium* species, and root condition of the trees. Physiographic factors exert a general influence on stand quality, but microsite variation in percent slope and aspect are critical components in the distribution of either symptomatic or asymptomatic trees within a given stand. These findings are similar to results reported by Shoulders and Walker (1979) and Zahner (1958). Slope percentage may have an effect on soil moisture where a gentle slope of less than 5 percent is optimal. A slope of 1 to 2 percent is optimal for tree growth and vigor; and a slope in excess of 5 percent causes a reduction in tree growth and vigor (Lorio and Hodges 1968, 1971, Lorio and others 1972). The data reported here support these findings and are the essential elements to the validation of LPDRM accuracy. The strong association with a vigor condition led to an accurate identification of microsite locations for selecting plots within the proper symptom treatment. Aspect appears to affect the soil temperature (Marshall and Holmes 1988) and soil water balance in high latitude regions (Hanna and others 1982), and was correlated with loblolly pine decline (Eckhardt and others 2007). The effects of slope and aspect may combine to create microclimates within microsites. Adverse (symptomatic) microclimates act as a predisposing disturbance that alone or in combination with other inciting disturbances reduce tree vigor. Accurate delineation of microsites using the LPDRM provided by this study can provide managers with the opportunity to mitigate some inciting disturbances and lower the risk of decline.

The accurate delineation of microsites and their predisposing effect on loblolly pine and commensurate vigor response provided the study with a biological association (growth parameters) for assessing the LPDRM. Evidence for pine growth decline in the Southeastern U.S. has been reported by the U.S. Forest Service, Forest Inventory Analysis (FIA) to have occurred over the last decade (Bechtold and others 1991, Gadbury and others 2004), although no casual factors where identified. Other studies investigating southern pine decline complexes have also reported reduction in growth parameters that can be associated with abiotic and biotic stress factors (Eckhardt and others 2007, Hess and others 1999, Otrosina and others 1999, 2002). These studies suggest that southern pines exhibiting reduced growth parameters are associated with a reduced vigor condition. The past decade has experienced extremely high southern pine beetle activity that can be associated with pines of reduced vigor (Blanche and others 1983, Hicks and others 1980, Schultz 1997). This suggests that there may be predisposing ecological conditions that reduce the health and vigor of pines across the Southeastern U.S. This study may have provided some elucidation of possible factors affecting reduced growth and vigor of pines. Reduced growth reported in this study was consistently associated with predisposing physiographic factors associated with varied tree vigor. Symptomatic plots that exhibited lower stem growth values appeared to be similar to other Southeastern U.S. sites that had reduced growth. Reduced growth and vigor were physiological conditions that were used to assess the presence of an abiotic site stress brought on by microsite factors. Poor crown conditions and lower resin production were significant factors in association with loblolly pine decline. Trees with large, dense crowns, and high resin production were associated with asymptomatic sites. In contrast, trees with small, thin crowns, and low resin production were associated with symptomatic sites.

Resin flow is the primary defense of pines against insect attack and fungal invasion (Bridges 1987, Hodges and Lorio 1975). Relative vigor can be associated with the amount of resin production by loblolly pine. Trees that produced more resin for a given measured time period had greater vigor at asymptomatic microsite locations. The trees on symptomatic plots showed lower resin production when compared with trees on asymptomatic plots (fig. 1). The aboveground symptoms of reduced radial growth, increased foliar transparency, decreased crown density, and reduced resin production (low vigor), were displayed by trees in the symptomatic plots but not in the asymptomatic plots. Trees in symptomatic plots also had deteriorated root systems. These results are consistent with results from studies of other pines associated with *Leptographium* species (Leaphart and Gill 1959, Wagener and Mielke 1961).

The decline of loblolly pine at FBMR appears to have resulted from the debilitation of root systems infected with *Leptographium* species associated with root-feeding insects attracted by the weakened condition of potential host trees influenced by stress or onsite disturbances. This finding is consistent with the findings in similar pine decline studies (Eckhardt and others 2007, Hess and others 2005, Klepzig and others 1991). *Leptographium* species and root-feeding insects were consistently associated with declining trees, and the damage apparent in the root systems was typically higher in symptomatic trees (table 4). This is consistent with observations made for other pines with *Leptographium* species activity in their roots (Eckhardt and others 2004, Klepzig and others 1991).

Total pest insect numbers showed a greater than two-fold increase over the 3-year study. The average daily catch per trap of 30 for southern pine beetle is considered epizootic, and in 2005 an average of 43 root-feeding beetles were collected per day per trap. This association indicates that root-feeding beetles may be at abnormally high populations (epizootic) and spreading infection by *Leptographium* fungi. These insects were found to be a significant contributing factor in the occurrence of loblolly pine decline on symptomatic plots. The overall average number of insects and the average number of insects associated with some type of plot disturbance (i.e. thinning, burning, and feral hog rooting) were higher in all symptomatic plots compared to the asymptomatic plots. The same pattern occurred when counts made from undisturbed plots were compared to single disturbance plots. Multiple disturbance plots had consistently higher average insect catches than single disturbance plots. These data indicate that higher numbers of root-feeding insects are significantly associated with a disturbance and further suggest that any increase in the number of disturbances to which a site is subjected favors further increases in the population of root-feeding insects. The association of root-feeding insects and *Leptographium* species on disturbed sites and the occurrence of loblolly decline suggest that disturbance mitigation may be a management option.

Five insect species (*H. picivorus*, *H. pales*, *H. salebrosus*, *H. tenuis*, and *D. terebrans*) occurred in higher numbers in symptomatic than in asymptomatic plots. This corresponds to the increased levels of associated beetle activity within stands having an elevated incidence of *Leptographium* species reported for declining loblolly pine in Alabama (Eckhardt and others 2007), for stands showing red pine decline in Wisconsin (Klepzig and others 1991), and for stands exhibiting black stain root disease caused by *L. wageneri* (Hansen 1978, Harrington and others 1985). These root-feeding insects were consistently associated with *L. terebrantis*, *L. procerum*, and *L. serpens* and may be serving as vectors of these, as well as similar, fungi in other disease complexes (Klepzig and others 1991, Rane and Tattar 1987). Insect damage alone was not found to seriously affect the trees, but the resulting colonization by the introduced *Leptographium* species was extensive. All of the pestiferous insects (five root-feeding bark beetle and weevil species) and other bark beetles and fungus-feeding insects have had *Leptographium* fungi isolated from them. Conidia are produced in sticky drops on the heads of conidiophores growing from fungal hypae within beetle galleries. New infections are initiated when contaminated beetles (from broods developing in diseased roots) are attracted to disturbed or stressed stands, dig through the soil in search of suitable roots for breeding and feeding, and bore into roots of living trees. The weakening and killing of root systems can provide enough susceptible hosts (brood substrate) to maintain high bark beetle populations over time (Eckhardt and others 2004). *Leptographium* isolates from root samples were collected on plots with high populations of root-feeding bark beetles and weevils that are aggressive in their feeding habits, thus creating new wound courts and opportunities for fungal invasion. At high population levels, the aggressive feeding activity of these bark beetles and weevils appears to have a major role in the occurrence of *Leptographium* species within areas of decline, as demonstrated by high insect numbers trapped with consistent *Leptographium* isolations from these insects (Eckhardt and others 2007). The insect numbers trapped were also significantly correlated with the degree of decline and root disease (Eckhardt and others 2007). The high pestiferous insect population and their association with *Leptographium* species were correlated with *Leptographium* pine root disease (Eckhardt and others 2007). This study confirms the similar findings for loblolly pine decline reported by Eckhardt and others (2007) and Hess and others (2005) and thus validated the potential of the LPDRM system as a useful tool for identifying and managing this disease.

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REGENERATION RESPONSE TO TORNADO AND SALVAGE HARVESTING IN A BOTTOMLAND FOREST

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Abstract—A direct hit from an F4 tornado on May 2003, followed by a partial salvage logging operation at Mermet Lake State Conservation Area on the Ohio River bottoms of southern IL have provided a rare opportunity to assess the responses of a bottomland hardwood forest to severe wind and soil disturbances. The study area encompasses 700 acres and is representative of many bottomland forests within the Mississippi Alluvial Valley in the influence of past agricultural clearing and present hydrologic management for waterfowl habitat on forest composition. Assessment of regeneration recovery was conducted during the first three growing seasons following salvage logging across a range of wind and logging-related soil disturbances. Regeneration density and percent stocking increased with wind disturbance intensity. No differences were found in stem densities between areas severely disturbed by wind, with and without harvesting.

INTRODUCTION

Natural and anthropogenic disturbances, such as wind and harvesting, need to be considered when formulating forest restoration and management strategies for bottomland forests. Accordingly, there is growing documentation regarding the effects of these on regeneration development (Aust and others 2006, Battaglia and Sharitz 2005). The present study considers the interaction of these two disturbances when they occur in rapid succession.

Wind frequently disturbs forests of the Middle Mississippi River Valley and is recognized as a driver of forest succession and composition (Peterson and Pickett 1995). In this region, tornadoes and linear winds are the dominant types of windstorms, frequently resulting in damage to a high percent of the canopy trees and creating large gaps. The vegetative response to wind disturbance is a function of wind intensity and gap size. Small gaps tend to release advance regeneration, often of shade-tolerant species. In larger gaps associated with severe disturbance, more shade intolerant species become established (Battaglia and others 1999, Battaglia and Sharitz 2005, Conner and Sharitz 2005, Webb 1989). Sprouts, originating from the bole or root collar of damaged individuals, also contribute to regeneration following severe wind disturbance (Peterson and Pickett 1991, Peterson and Rebertus 1997). Battaglia and Sharitz (2005) found that in forests with some level of disturbance, species from all categories of shade tolerance were present, contributing to higher species richness on disturbed sites.

Harvesting has been a major source of disturbance in bottomland forests since European settlement (King and others 2005, Whitney 1994). The effects of harvesting on bottomland forest regeneration are similar to wind disturbance, as density and species richness often increase with disturbance intensity (Aust and others 1992, Jansson and Johansson 1998, Reisinger and others 1988). A number of studies following clearcutting with skidder removal or simulation, indicated regeneration of preferred commercial species were favored (Aust and others 2006, Hassan and Roise 1998, Jones and others 2000).

Regenerated stands were similar in composition to both pre-wind and pre-harvesting-disturbed communities(Aust and others 2006, Battaglia and others 1999, Peterson and Pickett 1995). Aust and others (1997) and Hassan and Roise (1998) found that following harvesting on bottomland sites, regeneration was adequate in skidded areas, and stump sprouting contributed significantly to regeneration (Aust and others 2006, Hassan and Roise 1998, Jones and others 2000, Perison and others 1997).

The objectives of this study were to assess the regeneration response of a bottomland forest to 1) wind disturbance intensity, with and without salvage logging; and 2) soil disturbance intensity associated with salvage logging within wind-disturbed sites.

STUDY SITE

The study area was located within the Mermet Lake State Conservation Area in Massac County, IL, (37°15’ 25”N, 88°50’30”W), near the northern limit of the Mississippi Embayment. The General Land Office survey of 1807 characterized this area as a cypress pond prior to Euro-American settlement [Illinois Archives. Land Records. Illinois survey field notes, 1849. Located in Southern Illinois University Carbondale Morris Library (microfilm)]. During the early 1900s, the site was subject to drainage and conversion to row cropping, which led to increased fire frequency. Partial hydrologic restoration occurred in 1957, and the site has been managed as a wildlife area since that time. Fire and timber harvesting had been absent since the onset of state ownership and disturbance other than seasonal flooding limited until approximately 400 acres of forested land was severely damaged by an F4 tornado on May 6, 2003. A salvage harvesting operation intended to remove merchantable material and restore access to hunters occurred from October 2003 to April 2004. Prior to May 2003, the study area supported a closed canopy bottomland hardwood forest dominated by *Quercus palustris* Muenchh. and *Q. phellos* L. Other important canopy species included *Acer saccharum* Marsh., *Carya ovata* (Mill.) K. Koch, *A. rubrum* L., *Ulmus rubra* Muhl., *U. americana* L., *U.*

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alata Michx., *Fraxinus pennsylvanica* Marsh., *Liquidambar styraciflua* L., and *Nyssa aquatica* L.

METHODS

In the summer of 2004, sampling was conducted at 96 plots located in a grid pattern across approximately 140 acres of the study site. The site treatment classified was as follows: 1) undisturbed (Undisturbed)—areas that appeared free of structural tornado damage and containing a closed canopy overstory ≥ 60 years old; 2) transitional wind damage (Transitional)—areas located at the edge of the tornado swath that sustained some wind damage but where a partial overstory remained; 3) wind damaged (Wind)—areas that received a direct hit from the tornado and sustained nearly complete overstory removed; and 4) wind damaged with salvage harvesting (Harvested)—areas that sustained the same damage as Wind, but where salvage harvesting occurred.

Each plot contained four 1/1,000 ac (0.0004047 ha) circular regeneration sub-plots located at each of the four primary compass points and centered eight feet from the plot center. In each sub-plot, all regenerating woody species > 2 ft in height and less than 2 inches d.b.h. were identified annually during May-June from 2004 through 2006 (first through third growing seasons).

Within the harvested treatment, intensity of soil disturbance was characterized for each sub-plot according to Aust and others (1998) and recorded as follows: Class 0—soil appeared to be undisturbed by traffic; Class 1—soil was obviously compressed by vehicular traffic but no ruts were formed; Class 2—soil was rutted (as evidenced by puddled soil) and rut depth < 8.0 inches; Class 3—soil was rutted (as evidenced by puddled soil) and rut depth ≥ 8.0 inches; and Class 4—soil was obviously churned and puddled with indication of liquid soil movement.

One way analysis of variance (ANOVA) of expected mean squares was used to examine stem density variations between treatments. Changes over time were analyzed using repeated measures ANOVA, with an unstructured correlation structure used, to determine effects of treatment, time, and treatment*time interactions. Tukey's HSD method was used for pairwise comparisons of means. A stocking rate of at least 50 percent of sub-plots within a treatment containing at least one stem of an overstory species was considered adequate.

RESULTS

Effects of Disturbance on Woody Regeneration

During the third growing season, woody stem regeneration densities were 4,590 stems/acre for the entire site, with potential overstory species comprising 58 percent of all stems. Treatment (DF = 3, 91; F = 9.86; $p < 0.0001$), time (DF = 2, 91; F = 11.47; $p < 0.0001$), and a treatment*time interaction (DF = 6, 91; F = 3.08; $p < 0.0086$) were significant effects on woody species regeneration densities. The interaction resulted from a greater increase in the mean stem densities in the Wind and Harvested treatments compared to the Undisturbed and Transition treatments (fig. 1) in the third year mean stem densities (DF = 3, 89; F = 8.36; $p < 0.0001$)

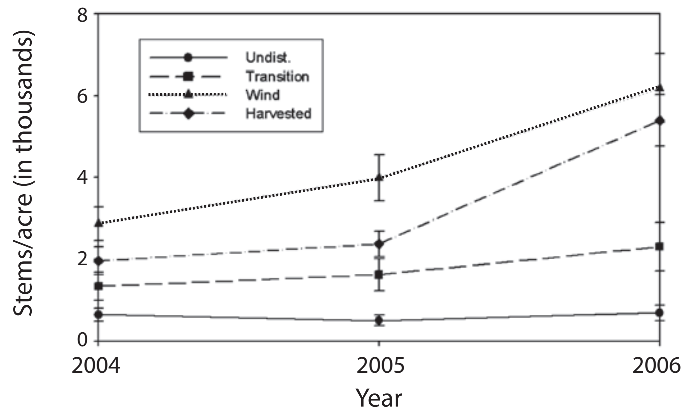

Figure 1—Stems per acre of all woody stems over first three years, by disturbance type.

(table 1). No difference in mean stem densities were detected between soil disturbance classes within the Harvested treatment (DF = 4, 46; F = 0.98; p = 0.4289).

Stem densities of overstory species regeneration increased with severity of wind disturbance (table 1). The Wind and Harvested treatments did not differ from one another but within the Harvested treatment, potential overstory stem density differed only between soil disturbance Classes 3 and 4. During the study period, regeneration of 36 potential overstory species was recorded, with green ash and red maple combined comprising nearly 50 percent of potential overstory species stems in the third year (table 2).

During the third growing season, 62 percent of all plots were stocked with at least 1 stem of a potential overstory species. Stocking levels increased with wind disturbance (table 3). Within the Harvested treatment, only soil

Table 1—Woody and overstory species regeneration stem densities during third growing season following salvage logging as a function of disturbance type

Disturbance type	Woody regeneration density (stems/acre)	Overstory species regeneration Density (stems/acre)
Undisturbed	687.5 a	625 a
Transition	2312.5 ab	1406 ab
Wind	6176.5 b	3309 b
Harvested	5394.2 b	3288 b

Means followed by the same letter within a column do not differ at 0.05 level.

Table 2— Species constituting ≥ 1% of overstory regeneration during the third growing season following salvage logging

Species	Percentage of stems (2006)
Acer negundo	3
Acer rubrum	26
Acer saccharum	3
Carya spp.	2
Celtis occidentalis	2
Diospyros virginiana	3
Fraxinus pennsylvanica	24
Liquidambar sturaciflua	7
Liriodendron tulipifera	3
Quercus spp.	3
Robinia psudoacacia	1
Sassafras albidum	4
Salix nigra	9
Ulmus spp.	6

Table 3—Percentage of sub-plots containing at least 1 seedling during the third growing season following salvage logging by disturbance type and soil disturbance class

Variable	Level	Percentage of plots
Disturbance type	Undisturbed	33
	Transition	50
	Wind	75
	Harvested	69
Soil disturbance class	0	85
	1	85
	2	71
	3	46
	4	65

Table 4—Dominant stem composition of stocked sub-plots during the third growing season following salvage logging

Species	All Plots with 1 stem (n=224)
Acer negundo	4%
Acer rubrum	19%
Acer saccharum	4%
Carya spp.	2%
Diospyros virginiana	4%
Fraxinus pennsylvanica	28%
Liquidambar sturaciflua	9%
Liriodendron tulipifera	6%
Nyssa aquatica	1%
Populus heterophylla	1%
Quercus spp.	5%
Robinia psudoacacia	1%
Sassafras albidum	4%
Salix nigra	7%
Taxodium distichum	1%
Ulmus spp.	6%
Total	102% *

* Total greater than 100% result of co-dominant stems in 9 plots

disturbance Classes 3 and 4 had stocking levels lower than Wind. Considering 50 percent stocking adequate, the only treatments not adequately stocked were the Undisturbed and soil disturbance class 3 within the Harvested treatment (table 3). Within stocked plots, nineteen different species served as the dominant stem, with F. pennsylvanica or A. rubrum the dominant stem in 47 percent of the plots (table 4).

DISCUSSION

Vegetation response was strongly related to disturbance intensity. These results are similar to those reported for other bottomland sites disturbed by wind or harvesting, where stem densities increased following disturbance (Aust and others 2006, Battaglia and others 1999, Battaglia and Sharitz 2005, Hassan and Roise 1998). Increased stem densities were also accompanied by an increase in diversity, with the number of species present increasing from Undisturbed to Harvested. This increase can be attributed to a reduction in competition and a shift from shade tolerant to shade intolerant species positively associated with an increase in disturbance intensity. The increases in total stem densities, species richness, and a shift toward more shade intolerant species is consistent with other studies of large gap formation (Battaglia and others 1999, Battaglia and Sharitz 2005, Hassan and Roise 1998, Peterson and Pickett 1995).

Early differences in stem densities between the Wind and Harvested treatments appear to be short-term. Rapid regeneration of the Harvested treatment was consistent with other research on bottomland sites (Aust and others 2006, Hassan and Roise 1998), as was the positive association between both stem density and diversity with disturbance intensity (Aust and others 2006, Battaglia and others 1999, Battaglia and Sharitz 2005, Hassan and Roise 1998, Peterson and Pickett 1995).

Within the Harvested treatment, tree regeneration density did not differ across soil disturbance classes. Further, the lack of a difference in stem densities between Harvested and Wind by the third growing season suggests that recovery from harvesting soil disturbance was occurring rapidly. This too is consistent with other studies on bottomland sites (Aust and others 2006, Hassan and Roise 1998).

During the third growing season, potential overstory species stem densities still differed between Classes 3 and 4, with Class 3 the only category where densities were not similar to or greater than those of the Wind treatment. An unexpected finding was that Class 4 not only had greater densities than the Wind area, but supported the highest densities of potential overstory species of any class. This area was associated with the most visually dramatic disturbance, as churning and liquid soil movement were associated with areas of nearly total devegetation. However, this high intensity of soil disturbance was associated with the establishment of high stem density, but lower diversity than all other treatments. Regeneration in Class 4 was dominated by light-seeded, moisture-tolerant species that benefit from wet, highly disturbed soil with little to no competition during their establishment period.

In the Harvested treatment, only Class 3 was considered to be inadequately stocked by overstory tree species. This is most likely due to extensive rutting (> 8 inches in depth) and compaction associated with extended periods of standing water throughout the year and limited establishment by even the most hydric species. However, even the severely impacted classes had relatively large increases in stocking by the second and third growing season, relative to the other soil disturbance classes. If this trend continues, the variations in stocking and stem densities between soil disturbance classes will continue to decrease, with Class 3 reaching adequate stocking in year 4.

CONCLUSION

Regeneration of overstory tree species occurred across the range of wind and salvage logging disturbance classes at Mermet Lake State Conservation Area. Variations in stem density and stocking levels among disturbance classes were observed during the first two growing season, but had diminished or were absent during the third growing season, suggesting these differences were transitory. Further analyses will address differences in species composition across the wind and harvesting disturbance gradients. Continued monitoring will be needed to determine how the regeneration cohort that has established following wind and soil disturbance responds to the post-agricultural hydrologic and fire regimes. The increasing presence of invasive species, such as Japanese stilt grass (*Microstegium vimineum*), Japanese honeysuckle (*Lonicera japonica*), and multiflora rose (*Rosa multiflora*) also appears to impact regeneration of native woody species in some areas and should be subject to continued monitoring.

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CONCEPTUAL FRAMEWORK FOR IMPROVED WIND-RELATED FOREST THREAT ASSESSMENT IN THE SOUTHEASTERN UNITED STATES

Scott L. Goodrick and John A. Stanturf[1]

Abstract—In the Southeastern United States, forests are subject to a variety of damage-causing wind phenomena that range in scale from very localized (downbursts and tornadoes) to broad spatial scales (hurricanes). Incorporating the threat of wind damage into forest management plans requires tools capable of assessing risk across this range of scales. Our conceptual approach involves breaking down the risk into components of event risk and resource vulnerability. Event risk can be simply stated as the probability of an event of a certain magnitude occurring in a given area and can be evaluated based on climatology. For wind related threats, resource vulnerability is determined by a complex function of stand and site characteristics. Although there is little that can be done to mitigate event risk, resource vulnerability can be manipulated through management activities. We have proposed a framework that includes a hierarchy of models for evaluating forest vulnerability to wind damage across a range of scales (from an individual tree, to a forest stand, up to the landscape scale); which, when combined with climatological models of event risk will provide a consistent wind-related threat-assessment tool.

INTRODUCTION

Forests are subject to a variety of damage-causing wind phenomena that range in scale from very localized (downbursts and tornadoes) to broad spatial scales (hurricanes). In the Southeastern United States all of these phenomena impact some portion of the region's forest on almost an annual basis. The magnitude of a wind-related disturbance is a complex function of the magnitude of the wind event along with topography, climate, and soil properties, as well as stand age, composition, and structure. To mitigate the threat of wind damage to southern forests requires an improved understanding of the disturbance process, which includes both the nature of the disturbance event (e.g., a hurricane) and the forest's response.

A hurricane represents the largest and perhaps most spatially complex of the wind-related disturbance events that affect southern forests. As a hurricane makes landfall, hurricane force winds, embedded squall lines, and associated tornadoes create a complex pattern of damage across a range of spatial scales—from a single tree up to an entire landscape (Boose and others 1994, Brokaw and Walker 1991, Walker 1995). The winds act to dissipate the energy of the storm by transferring it to the trees, which respond by swaying, twisting, and rocking; transferring energy down to the ground as well as to other trees (Drouineau and others 2000, Ennos 1997, Peterson, 2000). The first part of the tree to sustain damage is the crown, as leaves and small branches are stripped by wind, entrained soil particles, blowing debris, and friction with other crowns (Brokaw and Walker 1991). As the crown becomes streamlined, larger branches may break off and cause damage to understory trees (Frangi and Lugo 1991). Ultimately, with sufficient energy input, individual stems may bend, break, tip (full or partial uprooting), or remain standing with root system unstable (possibly broken loose from soil contact).

Stanturf and others (2007) present a conceptual approach to incorporating disturbance into forest management, using Hurricanes Katrina and Rita as example disturbance events. This paper builds on that work by providing a first step towards developing a system for assessing wind-related threats to southern forests. While the methodology is described for hurricanes it can be applied similarly to other wind threats such as downbursts and tornadoes. Ultimately this wind threat assessment will be combined with similar risk assessments of other threats such as ice storms, drought, insect or disease outbreaks, and invasive species to provide a comprehensive view of threats to southern forests.

APPROACH

Our approach to assessing wind-related threats involved separating the significance of an event (outcome risk) into the risk of a hurricane of some magnitude occurring (event risk) and the vulnerability of forest resources to that event (resource vulnerability) (Pielke and others 2005, Sarewitz and others 2003). For wind-related weather events, the event risk component cannot be affected directly by managers, but it is important to understand the frequency and variability of these events, especially when associated with severe weather such as hurricanes and other wind-related disturbances. For natural ecosystems such as coastal forests, resource vulnerability to wind-related disturbances, such as hurricanes, is a complex function of stand and site characteristics, which are largely independent of event risk (Pielke and others 2005). While event risk represents that portion of the overall risk that is beyond human control, resource vulnerability can be manipulated by management activities that may reduce the outcome risk.

Event Risk

In the case of hurricanes (or any other wind-related disturbance) event risk is a measure of the frequency of an event of some magnitude in an area, and it necessitates the development of a climatology. A first-cut hurricane climatology for examining forest wind damage is represented by the tracks of major (Category 3 through 5) hurricanes making landfall in the United States (fig. 1). These storm tracks were obtained from NOAA's HURDAT data set for

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1851-2005 (Javeinen and others 1984). For each tropical cyclone (hurricane), this data set contains information on location and intensity (maximum winds and minimum central pressure) every six hours as determined in a post-storm analysis. While storm tracks do provide a history of tropical storm activity in the Atlantic basin, they lack the spatially explicit wind information required to estimate the event risk for hurricane-strength winds in forests.

One means of obtaining a spatial wind field from the HURDAT information is to use a parametric hurricane model that describes the radial distribution of winds about a storm's center. Holland (1980) introduced a simple axisymmetric model that describes a hurricane based upon cyclostrophic balance between the wind and pressure fields as

$$P(r) = Pc + (Pa - Pc)\exp^{-(R\max/r)^B}$$

$$V(r) = \left[\frac{B}{\tilde{n}}\left(\frac{R\max}{r}\right)^B (Pa - Pc)\exp^{-(R\max/r)^B} + \left(\frac{rf}{2}\right)^2\right]^{\frac{1}{2}} - \frac{rf}{2} \qquad (1)$$

where P(r) is the pressure as a function of radius (r) from the storm center, Pc is the central pressure, Pa is the ambient pressure, Rmax is the radius of maximum wind, B is a storm profile parameter, V is the wind speed at r, ρ is the density of air, and f is the Coriolis parameter. Although this model is axisymmetric—that is, it predicts an equal wind speed distribution in all quadrants of the storm—actual hurricanes are not symmetric about their axis, particularly at landfall (Houston and others 1999). Georgiou (1985) added a modified form of the velocity equation that includes storm motion to introduce asymmetry into the Holland model. This simple model has been found to produce reasonable descriptions of hurricane wind distributions once appropriate values for Rmax and B have been determined. Vickery and others (2000) present equations to represent these values as functions of central pressure and latitude.

The Holland model is only appropriate for tropical cyclones over the ocean; it does not include the influence of changes in land surface or topography. During landfall, changes in surface roughness increase surface friction which reduces wind speeds and alters wind direction. In a similar parametric hurricane model, Boose and others (1994) simulated land fall by introducing a friction parameter that reduced wind speeds by 20 percent over land and increased the cross-isobar flow angle from 20 to 40 degrees. Realistic topographic effects are difficult to simulate in these simple parametric models. Boose and others (1994) employed a simple topographic sheltering effect that provided a basic means of determining areas that may be protected from damaging winds from a certain direction.

In the present study, the model of Georgiou (1985) with the parameter estimates of Vickery and others (2000) and landfall formulation of Boose and others (1994) is used to describe the hurricane wind fields. This approach is preferred over that of Boose and others (1994), because the hurricane model is completely described by parameters contained in the HURDAT data set (location, central pressure, and

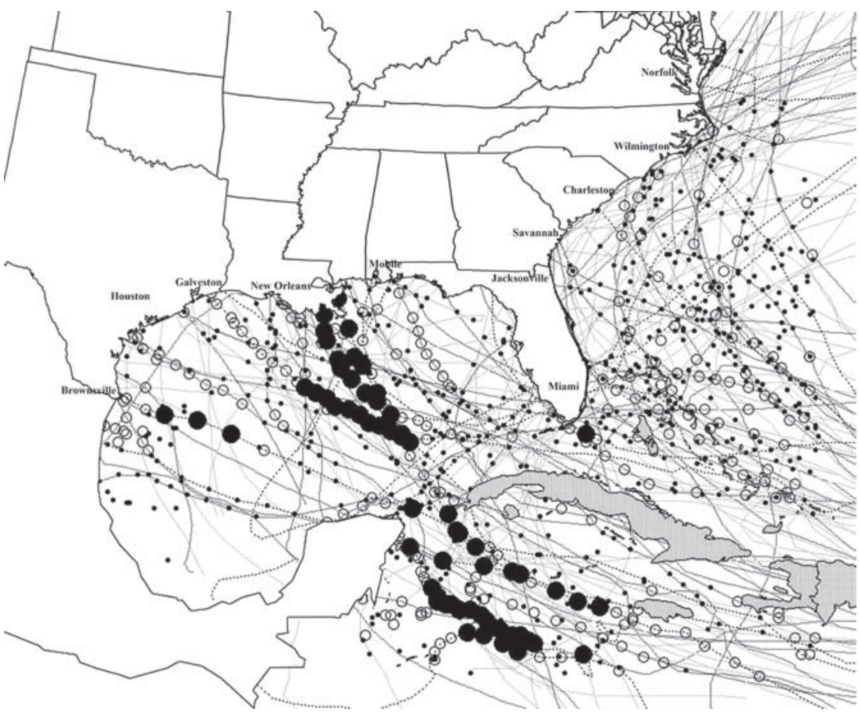

Figure 1—Major (Category 3-5) hurricanes making landfall in the eastern United States (1851-2005). The circles represent storm intensity during storm lifetime (small filled circles are Category 3, large open circles are Category 4, and large filled circles are Category 5). The tracks are for those storms that were Category 3 to 5 at some point in their lifecycle. The hurricane track map is from NOAA's HURDAT data set for 1851-2005 (Source: Jarvinen and others 1984; figure adapted from Stanturf and others 2007).

maximum sustained winds). The model of Boose and others requires specification of the storm's eye wall radius which is not available for historical storms and would otherwise need to be estimated from satellite imagery. While this approach is possible for modern-day hurricanes, it cannot be determined for the historical hurricanes that are needed to construct a climatology. Figure 2 shows a sample wind field for hurricane Katrina on August 28, 2005 when the central pressure dropped to 902 mb and maximum sustained winds peaked at 175 mph. The composite of maximum winds for Katrina determined by the model are shown in figure 3.

A coarse-scale hurricane wind climatology will be developed by creating daily 10 km spatial resolution grids of tropical storm winds for all tropical storm days in the HURDAT data set for which sufficient storm information is present to run the model. The spatial domain of the climatology must be sufficient to cover the Atlantic and Gulf of Mexico coasts of the United States. The temporal resolution of the climatology will match the six-hourly reports of the HURDAT data set. The grids for each time period will be composited to provide information on mean tropical storm force winds and frequency of occurrence for various threshold wind values. This re-creation of historical tropical storm winds will provide a broad view of hurricane winds, but does not provide the detailed wind fields required for examining disturbance at the stand or individual tree scales. In the future these scales will use a multilayer boundary layer model forced by initial and boundary conditions from the climatology to examine more closely the influence of land cover changes and topography.

Resource Vulnerability

In the case of wind-related disturbances, resource vulnerability can be simply stated as the likelihood that winds of a given magnitude will cause damage to the forest. If only determining this vulnerability were as easy as defining it. Vulnerability to wind damage is a complex function of more than just wind speed, because factors such as stand age, structure, and composition must be considered along with soils, topography, climate, and management history. In this first pass at assessing resource vulnerability, we recognized the need to consider potential stem breakage as a function of sustained wind speed, tree height, and tree spacing.

The simulation applied to loblolly pine (Pinus taeda L.) and longleaf pine (P. palustris Mill.) followed the methodology of the GALES windthrow model, with most parameters set for Pinus sylvestris L., Scots pine (Gardiner and others 2004). Species-dependent streamlining of the canopy is neglected here as wind tunnel data for the southern pine species used were unavailable; the canopy of each species of pine was treated as Scots pine. Nine hypothetical stands were created from combinations of three tree heights (20, 25, and 30 m) and three spacings (2.5, 5.0, and 7.5 m). For each of the nine stands the maximum bending moment at a height of 1.3 m above the ground was determined for both the interior of the stand and its edge; results were compared to the

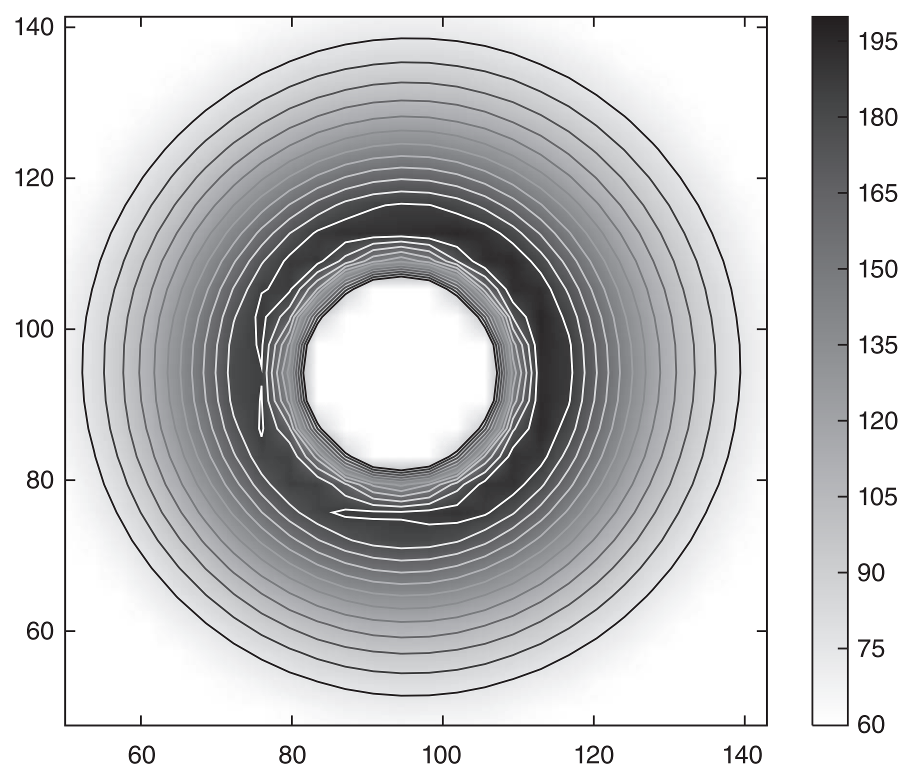

Figure 2—Simulated wind speed distribution for hurricane Katrina on August 28, 2005. At 12 GMT peak winds were 175 mph. Contours range from 60 to 170 mph with an interval of 10 mph. The x and y axes represent distance in kilometers. Note that this image is zoomed in on the hurricane and therefore shows only a fraction of the model domain.

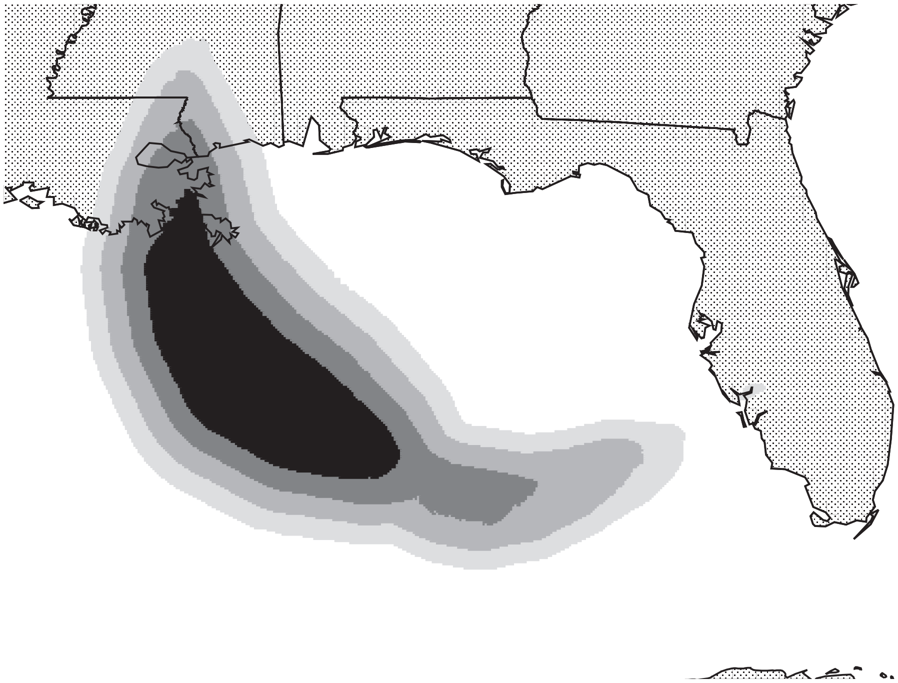

Figure 3—Simulated wind field for hurricane Katrina showing distribution of winds for Saffir-Simpson scale categories 2-5 (darker shades are higher intensity categories).

bending moment that signifies stem failure for both longleaf and loblolly pine species. For the interior portion of the stand (fig. 4), tree height was a primary factor in determining stem failure. At stand edges (fig. 5), the threshold for stem breakage was much lower, and tree spacing appeared to be a more important factor in avoiding wind damage than tree height, suggesting that managers may be able to reduce losses due to wind damage by altering planting densities along stand edges.

Note that we looked only at stem breakage for individual trees and not damage due to uprooting of trees; therefore, these modeling results are intended only as an illustrative tool rather than a detailed, species-specific study of tree failure. For a full assessment of wind-related disturbance vulnerability, the GALES model will need to be combined with a model for determining the resistive turning moment of the root-soil system (Lundstrom and others 2007) in order to fully describe the vulnerability of individual stems. Further

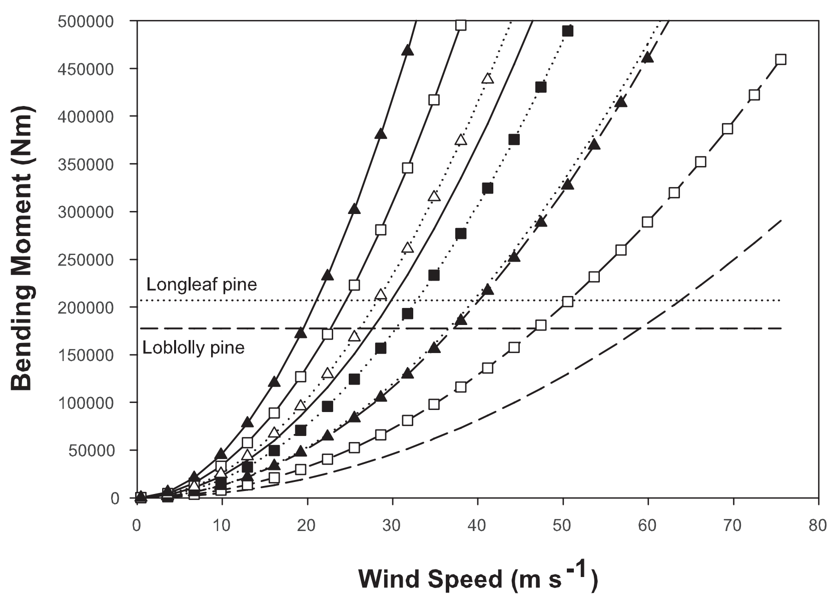

Figure 4—Bending moments of trees at the stand interior as a function of wind speed. Dashed, dotted, and solid curves represent 20-, 25-, and 30-m-tall trees; curves with no symbol are closed stands (tree spacing of 2.5 m); squares symbols represent semi-closed stands (spacing of 5 m); and triangles are open stands (spacing of 7.5 m). (Adapted from Stanturf and others 2007).

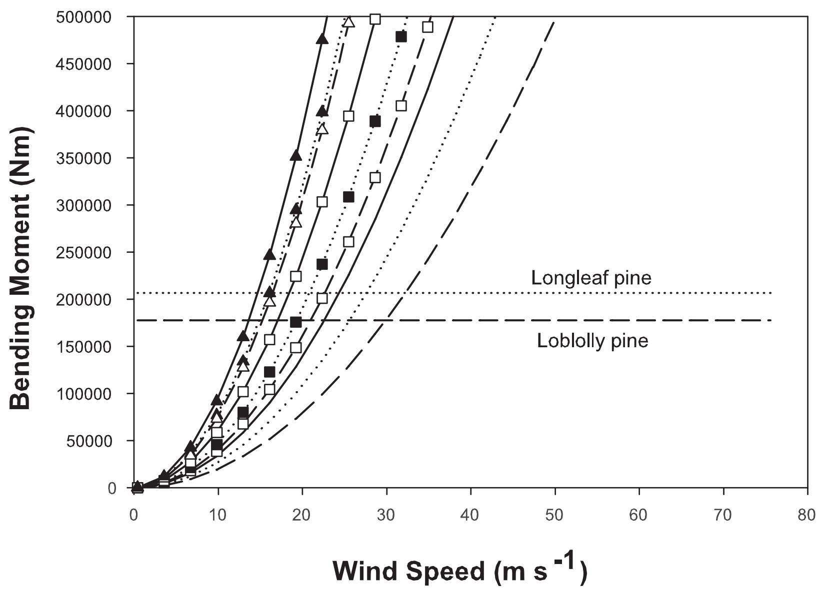

Figure 5—Bending moments of trees at the stand edge as a function of wind speed. Dashed, dotted, and solid curves represent 20-, 25-, and 30-m-tall trees; curves with no symbol are closed stands (tree spacing of 2.5 m); squares symbols represent semi-closed stands (spacing of 5 m); and triangles are open stands (spacing of 7.5 m). (Adapted from Stanturf and others 2007).

refinements will be needed to examine interactions among trees within a stand. Additionally, parametric uncertainty requires that distributions of the various input parameters for both the wind field model and the windthrow model will need to be developed in order to cast the wind-damage problem in terms of failure probabilities.

SUMMARY

This paper presents first steps in developing a framework for building wind-related threat assessment for southern forests. The first level, coarse-scale assessment tools (a hurricane wind climatology and GALES windthrow model) have been described. Next steps will involve improving the wind fields by adding of a three-dimensional boundary layer model to better capture the flow transitions that occur with landfall and topographic interactions. Extending the resource vulnerability component to include overturning as well as stem breakage will provide a broader view of forest vulnerability. Ultimately, the tools for evaluating event risk and resource vulnerability will be linked through a GIS to allow managers to plan and experiment with various management strategies.

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SOUTHERN PINE BEETLE INFESTATION PROBABILITY MAPPING USING WEIGHTS OF EVIDENCE ANALYSIS

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Abstract—Weights of Evidence (WofE) spatial analysis was used to predict probability of southern pine beetle (*Dendroctonus frontalis*) (SPB) infestation in Angelina, Nacogdoches, San Augustine and Shelby Co., TX. Thematic data derived from Landsat imagery (1974–2002 Landsat 1–7) were used. Data layers included: forest covertype, forest age, forest patch size and percent slope. WofE predicted infestation probabilities were significantly higher at infestation locations, versus random locations (p<0.0001). Significantly more infestations occurred in the higher probability areas (p=0.002). Infestation size was not significantly correlated with probability (p=0.0528). Correlations were found between WofE probability and traditional SPB hazard rating, calculated from forest inventory data, using the Mason (1981) system (p<0.0001). WofE probability maps were used to produce current SPB three and five-class hazard rating maps for the study area. WofE was effective for predicting SPB hazard, utilizing existing, remotely-sensed data sets.

INTRODUCTION

The southern pine beetle (SPB) (*Dendroctonus frontalis*) is the most destructive insect pest in the southern forest, (Price and others 1990, Thatcher and others 1980) causing an estimated loss of $265 million in 2001 and $364 million in 2002 (SFIWC 2002, 2003). Historically, SPB populations, and therefore damage, have been high in east TX (Coster and Searcy 1980, Pase 2001).

Predicting where, when and how severe SPB will strike is problematic. Beetle outbreaks are difficult to predict; the best way to reduce loss (hazard) is by determining areas most vulnerable to infestation, then concentrating detection and hazard reduction efforts on the most susceptible areas. Preventing conditions favorable to outbreaks is paramount. Hazard rating models are used to identify forests with characteristics indicative of susceptibility to pests. Hazard maps aid hazard reduction programs by identifying susceptible areas to apply practices for reducing susceptibility.

Numerous systems have been developed to rate stand susceptibility to SPB infestations (Coster and Searcy 1980, Mason and others 1985). Most of these systems are similar; utilizing specific site and stand characteristics to estimate susceptibility to SPB attack. The majority use landform, soil productivity and/or stand density as factors (Mason and others 1985). Major drawbacks are lack of availability of necessary data and poor resolution of hazard maps produced. Past rating systems produced maps with resolutions too poor to be used to identify small individual, yet high-hazard stands, especially those on non-industrial private forest landholdings (NIPF). Many past hazard rating systems have been unable to distinguish between high, moderate and low hazard areas within these “patchworks” of small parcels. Maps often produced generalized hazard ratings reflecting “average” condition among NIPF parcels and stands that were not useful for the small landowner in hazard rating of their individual property. Molnar and others (2003) studied the SPB hazard reduction practices of NIPF landowners, finding one of the key reasons for not performing these practices was lack of knowledge about the problem. Their findings indicate need to identify and educate owners of high-hazard properties. Although past systems were useful for landscape-level hazard rating and identifying specific regions for cultural activities, they have not been useful to the owners of nearly 142 million acres of NIPF land in the Southeastern United States (Wear and Greis 2002). High-resolution (satellite) data, combined with rapid processing ability of today’s geographic information systems (GIS) allow production of hazard maps helpful for even the smallest forest stand.

In 2003, the Research, Development and Applications Agenda for a Southern Pine Beetle Integrated Pest Management Program stated that forest and SPB managers, in general, “…have inadequate knowledge of the usefulness of remote sensing technologies to detect SPB infestations and identify susceptible conditions.” They recommended future research address the following: 1) “…tools to help determine where and which silvicultural protocols should be applied to prevent or reduce SPB-caused impact;” 2) “…more effective methods for monitoring susceptible forest conditions;” and, 3) “SPB hazard and risk assessment protocols improved to enable application at all relevant spatial and temporal scales” (Coulson and others 2003). We incorporate the use of Weights of Evidence spatial analysis (WofE) to address these research recommendations inclusively, in a manner not exhibited by previous systems. According to Coulson and others (1988) traditional hazard rating systems are problematic in they are not tied to a GIS, complicating map production and slowing the process of updating hazard ratings. This system is incorporated directly into a GIS, allowing for timely processing of more complex (and highly predictive) data, rapid hazard updates and efficient map production. WofE produced hazard rating maps, for a larger geographic area, at substantially higher resolution, than are produced by other models.

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OBJECTIVES

The main goal was to develop a GIS-based SPB hazard rating system using WofE analysis. The objective was to create a GIS that accurately rates forest stand susceptibility to SPB attack. Data more quickly and efficiently obtained by remote sensing and satellite imagery were used, rather than more time consuming field measurements or photogrammetric interpretation. The final product is a thematic map, predicting probability of southern pine beetle infestation for Angelina, Nacogdoches, San Augustine and Shelby Counties, TX, developed using remotely sensed data. This map could be utilized for SPB prevention and detection by effectively reducing the area in which to concentrate these efforts.

METHODS

The SPB infestation probability model was developed for Angelina, Nacogdoches, San Augustine and Shelby Counties, TX. Total land area is approximately 2.1 million acres (0.85 million ha), of which 1.6 million acres (0.63 million ha) are forested. Forestland ownership is approximately 84 percent private, 16 percent federal, state and local government (USFS FIA 2005). Two national forests (Angelina and Sabine), and two wilderness areas (Turkey Hill and Upland Island) are within the study area.

Weights of Evidence analysis was used to develop SPB occurrence probability maps. WofE has been used extensively for mineral potential mapping, and many other applications, however it had not yet been employed for forest insect hazard prediction. WofE is a data-driven, Bayesian model for spatial analysis, which utilizes multiple input layers and known occurrence locations to calculate the odds of the occurrence in a different geographic or temporal extent. ESRI ArcView® Spatial Data Modeler (Arc-SDM, available for download from http://ntserv.gis.nrcan.gc.ca/sdm/default_e.htm) extension was used to perform the analysis. Resulting probability maps were tested for effectiveness in accurately predicting probability of SPB occurrence.

Acquisition, processing and/or interpretation of numerous existing geographic datasets were required. Data were processed and converted into necessary formats using ESRI ArcMap® (9.0), ArcView® (3.3) and Leica Imagine® (8.7) software. The following GIS data layers, for the years 1992 and 2002, of Angelina, Nacogdoches, San Augustine and Shelby Counties, TX were acquired: forest cover type, forest age, forest patch size, slope percent, SPB occurrences for training data, and a grid of the study area. Forest cover type and age data were derived from Landsat 1–7 MSS, TM and ETM data. Forest patch size was produced by assuming a "clump" of forest the same age and cover type were a "patch." Percentage slope was derived from a USGS 30-m digital terrain model.

A point dataset for all recorded SPB infestations (10 trees or larger in size) in the study area for 1992 were obtained from the Texas Forest Service (TFS), Forest Pest Management, Lufkin, TX. The year 1992 was chosen for model building because it is the most recent year of substantial SPB activity in the study area corresponding with available forest type and age datasets. Half of the training points were selected randomly for use in training the model; remaining points were used to test the model's effectiveness.

Weights of Evidence Analysis

Step-by-step procedures for WofE analysis, found in Arc-SDM Users' Guide (Kemp and others 2001) were followed. Weights first were calculated for each data layer. The resulting weights then were used to evaluate usefulness of each data layer and to determine if classes were grouped appropriately. In order for examination of how strongly a theme is associated with SPB infestations, ArcSDM automatically generalized theme weights into a table of contrast values. Contrast values are not used to generate the predicted probabilities, yet are a general indicator of a themes overall positive (+) or negative (-) association with point occurrences.

Once weights were calculated and all themes evaluated, the response theme (Unique Condition Grid) was produced. This grid is a combination of weights from all evidential themes and may be displayed as a map of infestation probability. Posterior probability was calculated as the natural log of the odds of an infestation occurring at random in a cell, modified by the weight calculated for each evidential theme. The response theme (posterior probability) then was symbolized as a map showing the probability of annual southern pine beetle occurrences.

Data Analysis and Map Evaluation

Analyses were performed to test hypotheses concerning the WofE results and to determine if the WofE model could be used successfully to predict Southern Pine Beetle hazard. The output data of interest (posterior probability) is a predicted probability of annual SPB infestation within that pixel. All hypotheses were tested at the alpha = 0.05 level. The 1992 probability map was analyzed and evaluated for effectiveness of accurately predicting probability of SPB occurrence. The additional one-half of SPB occurrence points not used in model development were used as a check for model evaluation.

The first test was for significant differences in predicted SPB occurrence probability between actual occurrence locations and randomly selected points. SAS® Enterprise Guide 3.0 Software (General Linear Model Procedure) was used to perform an analysis of variance (ANOVA), to determine if predicted probability values were significantly greater at actual SPB occurrences than points selected at random.

The next test was conducted to determine if number of SPB occurrences was correlated with predicted probability. Poisson regression analysis originally was chosen because it is most suited for testing for randomness (inverse of correlation) where probabilities of occurrence are small (Zar 1999). SAS® 9.1 software GENMOD procedure was used to perform analyses. Poisson analysis indicated data were not distributed randomly. Lack of randomness may be due to what Zar (1999) referred to as contagious or overdispersed data, indicated by goodness-of-fit values greater than degrees of freedom (98 > 64). Contagious data are clumped, rather than distributed randomly across the landscape. Contagious data may be described by the negative binomial distribution; therefore a negative binomial regression was performed to again test the hypothesis (Zar 1999) (SAS® 9.1 software GENMOD procedure).

The 1992 probability maps were converted into more traditional 3- and 5-class SPB hazard maps. A five-class hazard map was produced by classifying predicted probabilities into five groups. The resulting group having the highest probability value was rated "very high hazard," each subordinate class rated respectively as follows: high, medium, low and very low hazard; a 3-class hazard map also was produced using the following classes: high, moderate and low hazard. These hazard maps then were evaluated, using the check points, in terms of number of occurrences/km2 for each hazard class.

Satisfactory results were obtained from the 1992 WofE analysis, therefore an up-to-date (2002) SPB probability map was generated by applying the developed model to current (2002) evidential themes. This current probability map was evaluated for effectiveness at predicting actual SPB hazard. Forest measurement data from 479 field sample plots (collected in early 2003) were used to hazard rate individual plot locations using methods described by Mason and others (1981). These calculated hazard ratings then were compared to the WofE predicted hazard rating. SAS Enterprise Guide® 3.0 software was used to perform Spearman's correlation analysis to determine if predicted WofE probability was correlated with actual hazard rating based on field measurements.

RESULTS

WofE analysis calculated a weight for each pixel of each evidential theme. This weight indicated the degree to which the pixel value is associated with training points. Weights were generalized as contrasts values; an average of all weights for a particular theme. Contrasts values indicate the degree to which each theme is associated with the training points. Contrast values for this study, listed in order of most, to least strongly associated, were; forest cover type (3.13), forest patch size (2.94), forest age (2.29) and percent slope (0.55). A contrast value of 3.13 for forest cover type indicates, on average, forest cover type 3.13 times more strongly associated with SPB infestation than would be expected with random probability. Contrast values indicated all evidential themes were associated positively with SPB infestations, with average values greater than expected at random; for all themes, except percent slope.

WofE analysis resulted in the calculation of posterior probability (probability of SPB infestation) maps, which are thematic maps with each pixel value indicating the probability of an annual SPB infestation for that pixel (pixel area = 100 m^2 or 1 ha). Probability values resulting from the 1992 WofE analysis ranged from near 0 to 0.15.

Next, effectiveness of WofE for predicting probability of SPB infestation, by comparing WofE results to actual SPB infestations was tested. The first test for the 1992 data was to determine if WofE predicted probability of SPB infestation was significantly greater for locations where SPB actually occurred versus randomly chosen locations. ANOVA results indicated WofE probabilities were statistically greater at actual infestation locations ($P<0.0001$). Mean probability values were 6.7 percent for infestations and 3.2 percent for randomly selected locations; predicted probability was over twice as great at actual infestations.

The second test of 1992 data was to determine if there were significantly more SPB infestations in the higher hazard areas than lower hazard areas. Actual SPB infestation density increased with hazard, from 0.022 to 0.101 spots/km^2, for the 5-class hazard map and from .030 to .067 spots/km^2, for the 3-class hazard map (table 1). For the 5-class hazard map, 20.8 percent of SPB infestations occurred on only 8.9 percent (very high hazard) of the total forested area. SPB infestation density ranged from 45.5 km^2/spot for very low hazard areas to 9.9 km^2/spot for the very high hazard areas. For the 3-class hazard map, 41.3 percent of SPB infestations occurred only on 26.6 percent (high hazard) of the total forested land area. SPB infestation density ranged from 32.8 km^2/spot for low hazard areas to 14.8 km^2/spot for the high hazard areas (table 1). Negative binomial regression was used to test for correlation between predicted probability and actual number of infestations (Zar 1999). This yielded a goodness-of-fit value of 57.936 (critical value 81.381) with $p=0.6907$, indicating the model had a good fit. This analysis also indicated probability was related significantly to number of infestations ($p=0.0002$).

Finally, current (2002) SPB occurrence probability and hazard maps were produced by applying the model developed for 1992 to current evidential themes. Results of this analysis produced a current (2002) SPB occurrence probability map. These maps also were visualized as 3- and 5-class hazard maps.

A final test was conducted on the 2002 WofE data. Since no current infestation data were available, correlation between predicted SPB hazard and SPB hazard calculated from forest inventory data was tested. Hazard ratings for 479 sample plot locations were calculated using the formula published by Mason and others (1981). The discriminant function values produced by this formula were compared to WofE predicted probabilities. Again, Spearman's test was used. Statistically significant correlations ($p<0.0001$) were found, with a correlation value 0.67. Although significantly correlated, when compared to Mason and others (1981) hazard rating, classification accuracy was only 34 percent exact agreement for the 5-class system and 55 percent for 3-class system. Direct (exact classification) assessment of accuracy potentially could be misleading. Mason's accuracy was approximately 78 percent and the results of the discriminant function analysis are condensed into classes. These factors considered, a weighted accuracy assessment was performed, which considered similarly classified points as well as points classified exactly the same (example: A point may have been classified low by Mason and very low

Table 1—Area, number of southern pine beetle (SPB) infestations, percentage of area, percentage of infestations and infestations per unit area for each hazard class (3- and 5- class SPB hazard maps) for forested and total areas (1992 Weights of Evidence analysis)

Hazard Class	Area (km^2)	% Forest Area	% Total Area	SPB Spots	% SPBs	Spots/ km^2	km^2/ Spot
Very Low	1772.9	29.2	49.2	39	14.8	0.022	45.458
Low	1571.9	25.9	18.5	63	23.9	0.040	24.951
Moderate	1034.5	17.0	12.2	40	15.2	0.039	25.863
High	1155.5	19.0	13.6	67	25.4	0.058	17.246
Very High	542.6	8.9	6.4	55	20.8	0.101	9.865
Total	6077.4	100	100	264	100		
Low	3345.0	55.0	67.8	102	38.6	0.030	32.794
Moderate	1115.0	18.3	13.2	53	20.1	0.048	21.038
High	1617.4	26.6	19.1	109	41.3	0.067	14.838
Total	6077.4	100	100	264	100		

by WofE; this is significantly better than if it were classified as high or very high by WofE). This resulted in a classification accuracy of 61 percent for the 5-class and 66 percent for the 3-class WofE hazard maps.

DISCUSSION

As expected, contrast values indicated forest cover type was most strongly associated with SPB infestations. Logically, SPB require pine hosts, therefore presence or absence of host trees is of critical importance. Contrast values indicated forest patch size was the second most strongly correlated theme, indicating importance of patch size for SPB, which has not been noted in previous studies.

Probability values, on average, were more than twice as high at locations where SPB infestations had occurred, versus randomly chosen locations. This result indicated WofE predicted probability is substantially higher where SPB occurred.

Correlation analysis of 2002 data indicated as SPB probability increased, calculated (Mason) hazard increased as well. Despite the statistically significant correlation, examination of data revealed some disparity between WofE and Mason hazard ratings. Hazard ratings were similar in the very low and low hazard classes, and slowly diverged as hazard class increased in severity. In general, misclassification occurred predominately as a commission error; that is, most WofE error resulted from over-rating SPB hazard. This over-rating of probability may have been due to conditional dependence among the datasets and the small number of infestations used for training data (Bonham-Carter 1996). However, rarely were points misclassified with WofE ratings lower than Mason's rating. Additionally, it should be noted, although the Mason hazard rating system is the standard rating system used in east Texas, it has a reported accuracy of only 71 percent (Mason 1979). Due to lack of an "exact" standard for comparison, a weighted assessment was performed, which gave consideration, not only to those points classified exactly the same, but also to those (at a lesser extent) whose values were similar. The resulting weighted accuracy was 61 percent for the 5-class and 66 percent for the 3-class hazard maps.

A cursory examination of forest measurements data and WofE evidential themes was conducted to determine if trends, in either data set, existed between misclassified points. Initial concerns were the WofE analysis lacked an estimate of stand density, which historically is important for hazard rating (Hicks and others 1980, Ku and others 1981). Average basal area of the13 most significantly misclassified (WofE very high class vs. Mason very low class) points was 28 square feet per acre (6.4 m^2/ha), which is nearly half as dense as the overall average of 42 square feet per acre (9.6 m^2/ha). Initially, this seemed to indicate disparity in classification was due to lack of consideration of stand density in the WofE analysis. Although the misclassification problem may be partially explained by stand density further examination revealed substantial variation in stand density among misclassified points (range from 0 to 144 square feet/acre or 0 to 33.0 m^2/ha). This variation could indicate another factor may be confounding the classification. Upon further examination, trends were found in both datasets; misclassified points were consistently in the >18 year age class with average tree heights less than 45 feet (13.7 m), with little variation. This trend seemed to indicate an inadequacy in the forest age dataset used in the WofE analysis. Mason and others (1981) classification of these points was rated very low due mainly to the tree heights less than 50 feet (15.2 m), yet WofE classified them as higher hazard, mainly because they fell into the >18 year age class. The misclassification problem created by the forest age dataset could be corrected. Data already are available to add a third age class (middle age class), resulting in three classes: <15 years, 15 - <25 years and ≥25 years, to the 2002 evidential themes. Future inclusion of improved forest age class data will be possible when current SPB infestation data becomes available to train the WofE model; i.e., the utility of the model should improve in the future.

WofE may predict hazard effectively, without producing exactly the same hazard estimates as traditional systems. It is quite possible WofE analysis considers variables and interactions not used in traditional hazard rating (such as forest patch size). Realistically, producing a SPB hazard map at a scale and resolution comparable to WofE, using the Mason system would be virtually logistically impossible. Mason's system, as well as many others, rates each stand separately, using extensive photo interpretation and/or ground-based measurements. Ultimately, the cost and time savings achieved by implementing a WofE system over a traditional system, could easily justify the possibility of over-estimating hazard of some stands. WofE hazard rating's effectiveness may not be tested truly until SPB infestations again occur in the study area. Although WofE may over-rate hazard in some areas, it effectively reduced the area for concentration of SPB detection and mitigation efforts. Reconnaissance efforts could be reduced to 20 percent of total area and 32 percent of forested area using the 2002 3-class hazard map, and 11 percent and 17 percent, of total and forested area, respectively, using the 5-class hazard map. The resulting cost-savings of using remote sensing to narrow SPB detection/reconnaissance efforts to the most likely infestation areas could be dramatic. WofE hazard rating also should prove to be an effective tool for hazard reduction education and/or cost-share programs, as it can aid in the identification of stands most in need of hazard mitigation.

CONCLUSIONS

WofE effectively, efficiently and rapidly produced high-resolution SPB hazard maps at a fraction of the labor, time and cost of traditional hazard rating systems. Past methods attempting wide-area (landscape level) hazard rating generally were successful, yet either failed to produce hazard maps at spatial resolutions useful to the land manager; or, required extensive, costly ground measurements and/or aerial photography interpretation (Billings and others 1985, Gumpertz and others 2000, Hicks and others 1980, Mason and others 1981, McNulty and others 1998). Weights of Evidence proved to be an effective method of predicting hazard of SPB infestations, at high-resolutions, utilizing existing remotely sensed datasets. This was accomplished without the use of extensive forest inventory or other labor-intensive practices, such as aerial photography interpretation.

Are WofE analysis hazard maps potentially useful for addressing the SPB problem in east Texas? The primary reason for NIPF landowners not implementing actions to prevent and control SPB was their lack of knowledge of the problem (Molnar and others 2003). Also, Cronin and others (1999) reported for control of SPB, area-wide management is necessary for localized control efforts to be effective. These two findings, when considered together, implicate usefulness of WofE analysis, or similar methods. Landscape-level data are needed in order to ensure hazard mitigation practices are applied area-wide; yet individual landowners need to receive information pertinent to their ownership. Despite shortcomings, Weights of Evidence SPB Hazard Rating can effectively address these issues simultaneously; provide broad, landscape-level hazard rating at a resolution useful to even the small NIPF landowner. WofE hazard maps are useful for identification of areas to concentrate mitigation, detection and educational efforts.

Technology is changing at a rapid pace. Many technologies presumed to be out of reach to the average landowner (and researcher) only a few years ago, now are available. Satellite imagery and other forms of remote sensing are more easily available, more affordable and increasing in resolution and quality. Most hazard rating systems were developed long before these data were readily available. As new data and technologies have become increasingly available most SPB researchers have attempted to extract data needed for existing hazard rating systems, rather than developing new methods utilizing the full potential of the data. Perhaps the time has come to explore using these current data and technologies in innovative new systems, rather than attempting to mold data into old methods. Research on utilizing remote sensing and spatial analysis tools, such as WofE, potentially will reduce the need for costly field data collection, while still providing much needed information about the health and condition of natural resources.

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FINANCIAL RATES OF RETURN ON THINNED AND UNTHINNED STANDS, USING LARGE-SCALE FOREST INVENTORY DATA IN MISSISSIPPI AND ARKANSAS, 1977 TO 1995

Andrew J. Hartsell[1]

Abstract—Providing landowners and natural resource managers information on financial rates of return (ROR) plays a vital role in providing and promoting forest management. I combined Timber Mart-South stumpage price data with forest inventory data spanning 17 years from the Southern Research Station, Forest Inventory and Analysis work unit for the States of Arkansas and Mississippi. This dataset was used to compute simple and adjusted financial ROR. The study area encompassed 63.4 million acres of which 37.4 million acres were in timberland. A total of 11 325 sample plots, of which 6 416 were classified as forest, made up the initial dataset. The study's timeframe spanned three decades, with MS surveys conducted in 1977, 1987, and 1994, while AR were in 1978, 1988, and 1995. Of these 6 416 plots, 245 were classified as sapling-seedling sized stands 1977 to 1978, sawtimber size 1994 to 1995, and having no harvesting or disturbance (< 5 percent all live removals or mortality) occurring on them at any time during the survey time span. Another 41 plots where classified as sapling-seedling sized stands in 1977 and had 20 to 50 percent of their all live volume removed during the 1987 to 1988 survey. These 41 plots had no harvesting, mortality, or disturbance during any other forest inventory and were classified as sawtimber size by the mid-1990s. I studied the annual rate of change (both monetary and volume) from the point which harvesting occurred on the thinned stands. Therefore, these preliminary results pertain to changes that occurred between the 1987 to 1988 and 1994 to 1995 surveys. The average annual volume growth of all live trees on the undisturbed plots was 2.2 percent per year, while the 41 thinned stands' volume growth was 4.6 percent per year. The average real ROR on the undisturbed stands was 15.7 percent per year using a simple financial maturity model, and 8.6 percent per year using an adjusted financial maturity model. The thinned stands grew at a higher rate, as their real rate of value change was 19.9 percent and 10.1 percent per year for the simple and adjusted financial maturity models, respectively. All volume and value change differences between undisturbed and thinned stands proved to be statistically significant. Combining long-term/large-scale forest inventories with price data has the potential to guide landowner decisions by offering insights into forest management dynamics.

INTRODUCTION

Duerr and others (1956) developed the concept of financial maturity, which is comparing the growth rate in timber values with an alternative rate of return. This idea can be adapted to any species and silvicultural system. Financial maturity is attained when the cost of holding an appreciating asset exceeds the expected monetary gains (Mills and Callahan 1979). Recently, data from the Southern Research Station (SRS), Forest Inventory and Analysis (FIA) unit have been used to calculate historical rates of return (ROR) on undisturbed forests across the South. These rates were compared to alternative investment options available to natural resource managers during the study timeframe (Hartsell 1999).

The next logical step in the process is to study the impacts of intermediate silvicultural practices, such as thinnings, using similar methodology. This paper investigates the financial impacts of thinnings using financial maturity concepts by combining FIA data with Timber Mart-South (TMS) stumpage prices. Two distinct datasets and time phases are analyzed. Comparisons will be made between thinned and unthinned stands over post treatment and rotation phases. Post treatment ROR compare thinned and unthinned stands for the survey period after the thinnings occurred, while the rotation ROR compare the rates of these for the entire study period.

STUDY AREA

The study area consists of all timberlands in the States of Arkansas and Mississippi. Timberland is defined as land that is at least 10 percent stocked by trees of any size, or formerly having such tree cover, and not currently developed for nonforest uses. Minimum area considered for FIA classification and measurement is one acre. The study area encompassed 63.4 million acres, of which 37.4 million acres were in timberland. A total of 11,325 sample plots, of which 6,416 where classified as forest, made up the initial dataset.

TIMEFRAME

The study's timeframe spanned three decades, with MS surveys conducted in 1977, 1987, and 1994, while AR were in 1978, 1988, and 1995. The study investigates two phases, posttreatment and rotation. Posttreatment ROR pertain to the change that occurred from the 1980s surveys to the 1990s. For thinned stands, this represents the change in value that occurred to the residual trees. The rotation ROR reflects the change that occurred between the initial stand and the terminal inventory.

METHODS

The data came from forest surveys of AR in 1978, 1988, and 1994, and MS in 1977, 1987, and 1994. The sample design utilized a two-phase method: dot counts for estimating timberland area and tree measurements on sample plots for determining stand and tree attributes. Sample plots were located on a 3-mile square grid. Each sample plot consisted of a 10-point satellite system covering about 1 acre. At each satellite point, trees were tallied by species along with diameter breast height (d.b.h.), height, and other tree-character variables for the determination of volume and biomass. Additionally, for each plot, stand level attributes

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were determined by computer algorithm for stand size and forest type.

PLOT SELECTION

All plots must be classified as forested for all survey periods in question. All 1970s plots had to be classified as poletimber size or smaller. All plots had to be sawtimber size and have at least 5 000 board feet per acre (International ¼-inch rule) in the 1990 surveys. Plots classified as unthinned had to have zero evidence of harvesting, management, or man-caused disturbance in either of the last two survey periods. This resulted in a sample size of 245 plots classified as unthinned (table 1). Plots classified as thinned had 20 to 50 percent of their all live volume removed between the 1970 and 1980 surveys, and no harvesting or management between the 1980s and 1990s surveys. Forty-one plots met the conditions for thinned stands. The distribution of these plots is illustrated in figure 1.

TREE SELECTION

All live trees ≥ 5 inches d.b.h. were included in the sample set, except rotten cull trees. Rough cull tree volumes were given pulpwood value. No cull trees were used in sawtimber computations. Tree selection was performed by variable radius sampling (37.5 basal area factor [BAF]). Since tree selection was performed by variable radius sampling, new trees appear over time. These new trees were included in all computations and therefore affect growth and value changes. Trees that died between survey periods were included only in the survey year(s) in which they were alive. This has the potential to create negative biological and economic value growth between surveys.

TIMBER MART-SOUTH DATA

This study uses TMS price data to calculate individual tree values. TMS has been collecting delivered prices and stumpage prices for 11 Southern states since December 1976. All TMS price data are nominal. Real prices were calculated using the U.S. Bureau of Labor Statistics all commodities producer price index. As 1987 was the midpoint of the study period, all TMS prices were inflated or deflated to 1987 levels.

TREE PRODUCTS AND VALUES

The algorithm used for determining tree products was: 1) all poletimber-size trees are used for pulpwood, 2) the entire volume of rough-cull trees, even sawtimber-size trees, is used for pulpwood, 3) the saw-log section of sawtimber-size trees is used for sawtimber, and 4) the section between the saw-log top and 4-inch diameter outside bark pole top is used for pulp and often referred to as topwood. Poletimber-size trees are softwoods 5.0 to 8.9 inches d.b.h. and hardwoods 5.0 to 10.9 inches d.b.h. Sawtimber-size trees are all softwoods that are

Table 1—Number of plots, average annual growth percent, real timber value growth, and real forest value growth percent of unthinned and thinned stands, post treatment period, in Arkansas and Mississippi, 1988 to 1995

Model	Number	Average	Std.dev.	Maximum	Minimum
		unthinned stands (percent)			
BGP[a]	245	2.17	3.86	13.23	-44.72
TVG[b]	245	15.66	7.38	38.80	-55.67
FVG 250[c]	245	10.87	4.44	21.35	-19.94
FVG 500[d]	245	8.62	3.72	18.75	-14.25
FVG 750[e]	245	7.22	3.28	16.75	-11.27
		thinned stands (percent)			
BGP[a]	41	4.60	3.27	13.20	-2.66
TVG[b]	41	19.86	6.98	36.68	8.33
FVG 250[c]	41	12.98	4.87	22.02	2.20
FVG 500[d]	41	10.10	4.31	19.97	1.27
FVG 750[e]	41	8.38	3.94	18.32	0.89

[a] BGP = the average annual change in volume expressed as a percentage.
[b] TVG = the unadjusted annual real rate of return.
[c] FVG = the adjusted annual real rate of return with land value = $250 per acre.
[d] FVG = the adjusted annual real rate of return with land value = $500 per acre.
[e] FVG = the adjusted annual real rate of return with land value = $750 per acre.

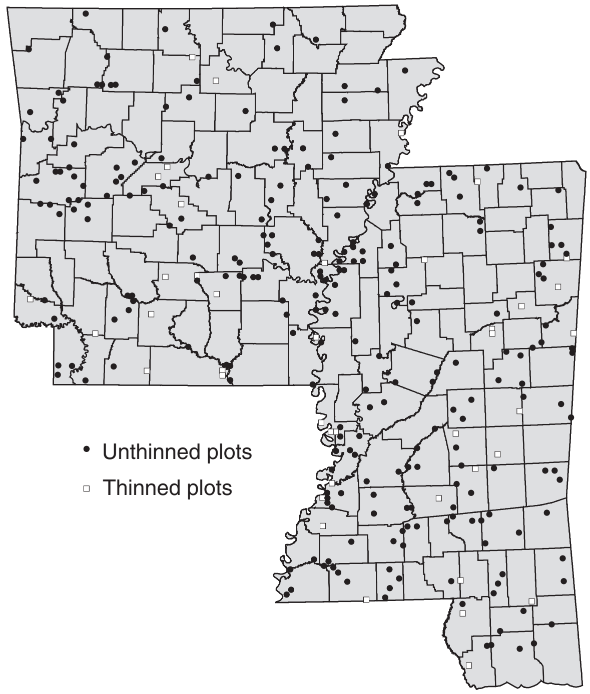

Figure 1—Distribution of unthinned and thinned sample plots in Arkansas and Mississippi.

at least 9.0 inches d.b.h. and hardwoods that are at least 11.0 inches. Cull trees are any tree that is less than one-third sound.

In 1981, TMS began to report southern pine chip-n-saw prices. Therefore, the two survey periods after this time included a third product, southern pine chip-n-saw. Chip-n-saw trees are southern pines 9.0 to 12.9 inches d.b.h. All trees < 9.0 inches are still treated as pulpwood and trees ≥ 13.0 inches d.b.h. are treated as sawtimber trees. This modification was made for the 1988 and 1995 survey periods.

FIA traditionally computes all board foot volumes in International ¼-inch log rule. Most of the TMS price data is in Doyle log rule. To accommodate the price data, all FIA tree volumes were recalculated using the Doyle formula. There are a few instances where prices are reported in Scribner log rule. To accommodate this, the Doyle prices for these few instances were converted to Scribner prices by multiplying the Doyle price by 0.75 (Timber Mart-South 1996).

The TMS reports include a low, high, and average price for standing timber for various products. This report does not consider peeler logs or poles and piling as possible products because determining these products from FIA data is questionable. Omitting these classes allows for a slightly conservative approach to estimating tree and stand value. FIA data has information on species, product size (poletimber or sawtimber), and quality (tree class and tree grade). Prices for each section of the tree were assigned based on these factors. These prices were then applied to the different sections of a tree.

GROWTH MODELS

Timber volumes and values are summed for each plot. These totals are then used as inputs for the growth models. Three growth models were used in this study. Each is based on the formula used in determining average annual change.

Timber value growth (TVG) is a simple financial maturity model that considers only the actual change in value for a plot for the survey period in question. Incomes derived from future stands are ignored (Hartsell 1999). The basic formula for TVG is:

$$FVG = \left[\left(\frac{TVF + LVF}{TVP + LVP}\right)^{1/t} - 1\right] \times 100 \qquad (1)$$

where

TVG = timber value growth percent
TVF = ending sum of tree value on the plot at time 2
TVP = beginning sum of tree value on the plot at time 1
t = number of years between surveys.

Forest value growth (FVG) includes the value of land in the computation of economic value change (Hartsell 1999). The formula for FVG is:

$$FVG = \left[\left(\frac{TVF + LVF}{TVP + LVP}\right)^{1/t} - 1\right] \times 100 \qquad (2)$$

where

FVG = forest value growth percent
TVF = ending sum of tree value on the plot at time 2
LVF = ending land value
TVP = beginning sum of tree value on the plot at time 1
LVP = beginning land value
t = number of years between surveys

FVG is an adjusted financial maturity model. Adjusted financial maturity concepts account for all implicit costs associated with holding timber. These are sometimes referred to as opportunity costs. In doing so, revenues from future stands are accounted for. One method of adjusting the model is to include bare-land value (LV) in the equation, because bare-LV accounts for future incomes and the inclusion of LV adjusts the simple financial maturity model. Further discussion on implicit and explicit costs, as well as the results of these studies, can be found in other studies by the author (Hartsell 1999).

Biological growth percent (BGP) is similar to TVG, except it uses timber volumes instead of timber values. The BGP model accounts for the actual annual change in tree volume for a plot over a survey period. The BGP model is the same as the TVG model, except it uses the sum of tree volumes on the plot instead of the sum of tree values (Hartsell 1999).

RESULTS AND DISCUSSION

Comparing posttreatment volume and value change rates between thinned and unthinned stands yields predictable results. Stands that had 20 to 50 percent of their all live volume removed in the 1970s grew more than twice as much as unmanaged stands between the last two surveys (mid-1980s to mid-1990s). Unthinned stands increased in total volume at a rate of 2.2 percent per year, while stands that where thinned in the prior survey grew at a rate of 4.6 percent per year. This indicates that the thinning produced an increased growth response, or release, for the remaining trees (table 1).

Financial ROR also favored thinned stands. The simple financial maturity model (TVG) shows that between the last two survey periods, thinned stands earned 19.9 percent per year, compared to 15.7 percent for unmanaged stands. These rates appear high for several reasons. The first is that there was a dramatic increase in real stumpage values that occurred in the late 1980s and early 1990s. Another is that the simple model fails to account for many of the implicit and explicit costs of holding timberlands. The adjusted models (FVG) account for these costs. FVG was computed for three different per acre bare-LV; $250, $500, and $750. Increasing bare-LV has a moderating effect of ROR. The adjusted ROR on thinned stands ranges from 13.0 percent per year to 8.38 percent per year depending on the value of land. All of these are higher than the adjusted ROR found on unthinned stands, which have ROR ranging from 10.9 percent per year to 7.2 percent. Additionally, all thinned stands produced a positive financial ROR, that is, no managed stand lost money. Conversely, at least one unthinned stand lost anywhere from 11.3 percent to 19.9 percent per year, depending on LV.

Stratifying the plots by forest type reveals that pine stands responded to the thinning, the greatest in terms of biological growth (table 2). Thinned pine stands accrued 5.8 percent per year in volume, compared to 4.0 percent per year for unthinned stands of the same type. Again, all thinned forest types outperformed their same type in the unthinned dataset. One would assume that due to this increase in growth, pine would outperform the other types in terms of financial growth as well. But this is not the case. Managed mixed and oak-gum-cypress stands had higher unadjusted ROR than thinned pine due to the dramatic increase in the stumpage prices of hardwoods that occurred during this time period.

Adjusting the simple model with $750 per acre yields different results, as pine stands are now ranked first in terms of ROR, earning 10.6 percent per year. This is significantly higher than mixed-stands' 8.5 percent per year. Oak-gum-cypress or oak-hickory stands (7.7 and 4.7 percent per year respectively) are the lowest earning types (table 2). The reason these pine stands earn more after the adjustment is simple. Pine stands in general had higher per acre values in the mid-1980s than hardwood stands. Over the next 10 years, hardwood stumpage prices rose faster than pine. This produced higher simple returns for hardwoods, as the starting value for these stands was low. However, adjusting the model had a greater moderating effect on hardwood stands due to this low initial stand value.

Tables 1 and 2 clearly illustrate the post-thinning response of forested stands in AR and MS. This raises the question: what is the economic impact of thinning for the entire "rotation," with rotation being the timeframe of the study (mid-1970s to

Table 2—Number of plots, average annual growth percent, real timber value growth, and real forest value growth percent of unthinned and thinned stands, post treatment period, by forest type, in Arkansas and Mississippi, 1988 to 1995

Forest type	Number	BGP[a]	Std. dev.	TVG[b]	Std. dev.	FVG 750[c]	Std. dev.
			unthinned stands (percent)				
Pine	32	3.97	2.58	16.41	4.63	8.59	3.21
Mixed	26	2.53	2.34	16.85	6.29	8.27	2.74
Oak-hickory	62	1.19	6.36	14.90	11.19	6.54	3.94
Oak-gum-cypress	117	2.09	2.40	15.83	5.74	7.01	3.00
Elm-ash-cottonwood	8	2.84	1.40	12.49	2.83	6.86	1.93
			thinned stands (percent)				
Pine	15	5.80	2.32	19.89	4.41	10.64	4.52
Mixed	5	3.29	3.11	20.34	6.63	8.49	2.05
Oak-hickory	7	3.85	3.89	17.59	11.37	4.72	3.17
Oak-gum-cypress	14	4.16	3.90	20.79	7.48	7.75	2.76

[a] BGP = the average annual change in volume expressed as a percentage.
[b] TVG = the unadjusted annual real rate of return.
[c] FVG = the adjusted annual real rate of return with land value = $750 per acre.

Table 3—Number of plots, average annual growth percent, real timber value growth, and real forest value growth percent of unthinned and thinned stands, entire study period, in Arkansas and Mississippi, 1988 to 1995

Model	Number	Average	Std.dev.	Maximum	Minimum
		unthinned stands (percent)			
BGP[a]	245	3.15	3.33	28.21	-22.29
TVG[b]	245	9.27	5.94	33.92	-28.47
FVG 250[c]	245	5.57	2.64	11.66	-7.46
FVG 500[d]	245	4.27	2.02	9.58	-4.96
FVG 750[e]	245	3.52	1.70	8.21	-3.76
		thinned stands (percent)			
BGP[a]	41	2.14	2.56	9.34	-3.31
TVG[b]	41	8.01	4.21	16.30	-1.09
FVG 250[c]	41	4.97	2.57	10.20	-0.94
FVG 500[d]	41	3.81	2.06	7.87	-0.83
FVG 750[e]	41	3.14	1.76	6.77	-0.75

[a] BGP = the average annual change in volume expressed as a percentage.
[b] TVG = the unadjusted annual real rate of return.
[c] FVG = the adjusted annual real rate of return with land value = $250 per acre.
[d] FVG = the adjusted annual real rate of return with land value = $500 per acre.
[e] FVG = the adjusted annual real rate of return with land value = $750 per acre.

mid-1990s)? These results were surprising and confounding. Initial post treatment period results indicated that unthinned stands grew more and earned more than thinned stands. Unthinned stands grew 3.1 percent per year versus 2.1 for thinned stands (table 3). Likewise, all economic ROR were higher for unthinned stands. The unadjusted ROR for managed stands was 9.3 percent, compared to 8.0 percent for managed forests. Adjusting the model with LV with $250, $500, and $750 per acre produced similar results.

ROR by forest type were then computed to determine if these results where due to species. This was not the case, as unthinned stands again outperformed thinned in every type group. Unthinned pine stands grew 5.2 percent per year, compared to only 3.5 percent for unthinned (table 4). The unadjusted model indicates that unthinned stands earned more than their counterparts for every type except mixed, which where statistically insignificant. Only after the model is adjusted with $750 per acre do thinned pine and mixed stands begin to compare to those that were undisturbed. Unthinned pine stands earned 4.4 percent per year (adjusted model with $750 per acre) which is comparable to 4.2 percent for the thinned stands.

The results from tables 3 and 4 caused a review of the methodology and models. It is quickly apparent that the models do not account for any tree volume and value that was removed during the thinning. Thus, the current models are reliable for studying the post management response to stands (tables 1 and 2), but lacking when dealing with entire rotations (tables 3 and 4). Therefore, conclusions drawn from the first two tables, thinning produces more growth and economic returns immediately after thinning, are correct. Tables 3 and 4 underestimate the returns from thinned stands, as incomes derived from the silvicultural operations are excluded. This is particularly revealing, because the adjusted ROR for pine and mixed stands were statistically

Table 4—Number of plots, average annual growth percent, real timber value growth, and real forest value growth percent of unthinned and thinned stands, entire study period, by forest type, in Arkansas and Mississippi, 1988 to 1995

Forest type	Number	BGP[a]	Std. dev.	TVG[b]	Std. dev.	FVG 750[c]	Std. dev.
			unthinned stands (percent)				
Pine	32	5.21	5.06	11.56	7.25	4.37	1.70
Mixed	26	3.42	2.59	9.73	4.99	4.07	1.51
Oak-hickory	62	2.27	3.74	8.14	7.08	3.07	1.95
Oak-gum-cypress	117	2.92	2.41	9.18	5.04	3.41	1.53
Elm-ash-cottonwood	8	4.23	1.87	8.60	4.65	3.58	1.44
			thinned stands (percent)				
Pine	15	3.49	2.83	9.35	3.95	4.22	1.78
Mixed	5	1.80	2.00	10.01	3.56	4.02	1.03
Oak-hickory	7	1.85	3.00	8.79	4.67	2.12	1.44
Oak-gum-cypress	14	0.97	1.77	5.48	3.80	2.17	1.37

[a] BGP = the average annual change in volume expressed as a percentage.
[b] TVG = the unadjusted annual real rate of return.
[c] FVG = the adjusted annual real rate of return with land value = $750 per acre.

insignificant to the unmanaged stands when higher bare-LV are used to adjust the models. To fully examine the long-term ROR on managed stands, the current models need to be modified to account for these revenues. Future studies will incorporate these factors.

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IMPACT OF INITIAL SPACING ON YIELD PER ACRE AND WOOD QUALITY OF UNTHINNED LOBLOLLY PINE AT AGE 21

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Abstract—The market for southern pine first thinnings is soft. Thus, forest managers are planting at wider spacings, and using weed control and fertilization to grow chipping-saw and sawtimber trees in shorter rotations. A 21-year-old unthinned spacing study was sampled to determine the effect of initial spacing on wood quality and yield per acre of planted loblolly pine (*Pinus taeda* L.). The study area was planted in the Coastal Plain of GA in 1984 with loblolly pine family 7-56 seedlings. Twenty-one trees from each of seven spacings ranging from 6 by 8 feet (908 trees per acre) to 12 by 12 feet (302 trees per acre) were sampled. Total stem green weight per acre of wood and bark to a 3-inch d.o.b top was estimated to be highest in the 6 by 12, 8 by 10 and 8 by 12 foot spacings. Estimated volume of lumber per acre was slightly higher in the 8 by 12 spacing compared to the 12 by 12-feet spacing. Breakeven stumpage price per acre was highest for the trees planted at 8 by 12-feet spacing. Average number of knots, knot diameter, and average maximum knot diameter increased with increased spacing.

INTRODUCTION

The demand for young, small diameter southern pine in the South is soft. Thus, forest managers are planting at wider spacings and using weed control and fertilization to grow chipping-saw and sawtimber sized trees in shorter rotations. Planting at wide spacing stimulates diameter and crown growth, which can result in larger diameter branches (Baldwin and others 2000, Sharma and others 2002). The diameter of knots is an important characteristic which can degrade southern pine dimension lumber and veneer (Clark and others 1994, Clark and McAlister 1998). Amateis and others (2004) examined the effect of spacing rectangularity on stem quality of plantation loblolly pine (*Pinus taeda* L.) and found that rectangularity had no significant effect on survival or number of potential sawtimber trees by age 19. However, they did report that a 1:3 spacing treatment had a significantly larger maximum branch diameter than the 3:4 spacing.

Some land managers are promoting low-density management, where trees are planted at 600 to 700 trees per acre, then thinned at an early age to 100 to 120 trees per acre and pruned to produce sawtimber at a young age (Burton 1982, Huang and Konrad 2004). Nonindustrial private forest landowners (NIPF) will find it difficult to obtain proper stumpage prices for pruned sawtimber grown under low-density management, because to maximize lumber value pruned logs should be sawn into shop lumber (Clark and others 2004). Thus, NIPF landowners need to establish their plantations at initial spacings that will maximize growth of chipping-saw and sawtimber trees with no early thinning or punning. Our study examined the effect of initial spacing on the yield of chipping-saw and sawtimber trees at age 21 in unthinned stands.

METHODS

We sampled a loblolly pine spacing study that was established on the Atlantic Coastal Plain in 1984 near Rincon, GA. The spacing study contained 11 spacings and each was replicated three times. The study was planted with loblolly pine family 7-56 seedlings on commercially prepared beds with 8 rows and 8 trees per row. At the time of planting each spacing plot was fertilized with 125 pounds of diammonium phosphate and herbaceous weeds were controlled with a broadcast application of herbicide. All plots were re-treated during the first and second years for herbaceous weed control and fertilized with 300 pounds of urea at ages 5 and 10.

Seven of the 11 spacings in the study were selected for sampling to represent a range of trees per acre. The spacings sampled include: 6 by 8 feet or 908 trees per acre, 6 by 10 feet or 726 trees per acre, 6 by 12-feet or 605 trees per acre, 8 by 10-feet or 544 trees per acre, 8 by 12-feet or trees per acre TPA, 10 by 12-feet or 363 trees per acre and 12 by 12-feet or 302 trees per acre. The diameter at breast height (d.b.h.) and total height (THT) were measured on all trees in each plot in the fall of 2004 (table 1). Seven trees were selected for destructive sampling from each plot in proportion to the d.b.h. distribution in the plot. The trees were felled in June 2005 and the height above ground and diameter of all live, dead, and overgrown knots to a 4-inch diameter outside bark (d.o.b.) top were recorded. If the knot was on the face of the stem within the row or between rows also was recorded. Stem height to a 5.5-, 4-, 3- and 2- inch d.o.b. was recorded and the d.o.b. at 17.3 feet also was recorded. Cross-sectional disks 1.5-inches thick were cut at stump, 4.5 feet and at 5 feet intervals up the stem to a 2-inch d.o.b. top. Stem diameter outside and inside bark (d.i.b.) were determined from the disks.

The Girard form class (FC) of each tree ≥ 8.0 inches d.b.h. was calculated based on d.i.b. at 17.3 feet and d.b.h. Stem green weight of wood and bark from stump to a 3-inch d.o.b. and stem weight from stump to a 5.5 inch d.o.b. top were estimated based on d.b.h. and THT using plantation loblolly pine weight equations (Clark and Saucier 1990). Estimated sawmill lumber tally by lumber grade was based on log small-end d.i.b., log length and log grade using unpublished cut log lumber yield equations developed by Clark (Alexander

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Table 1—Average tree characteristics and surviving tree count by initial spacing at age 21

Spacing	Initial TPA	d.b.h. Average	d.b.h. Range	Total Height Average	Total Height Range	Trees < 8.0 inch d.b.h.	Trees ≥ 8.0 inch d.b.h.	Total trees surviving	Proportion trees surviving
feet	*No.*	*inch*		*feet*		*No./acre*	*No./acre*	*No./acre*	*%*
6X8	908	7.7	2.8-13.8	72	25-89	321	265	586	65
6X10	726	8.4	4.6-12.8	76	52-91	221	278	499	69
6X12	605	8.7	4.1-13.1	75	42-91	165	340	505	83
8X10	544	9.3	5.3-15.5	77	52-90	119	318	437	80
8X12	454	9.7	4.0-14.4	80	36-94	54	333	387	85
10X12	363	10.2	5.7-13.6	81	55-94	31	295	326	90
12X12	302	11.0	3.2-16.4	81	29-92	19	254	273	90

Clark III, Southern Research Station, 320 Green St, Athens GA). Sawlog grade was based on small-end d.i.b. and maximum knot diameter in the log. Log lengths were assumed to be 16.3 feet starting at the base of the stem and 8.3 feet for the top log when log length for the top log was less than 16.3 feet to a 5.0-inch d.i.b. top. Small-end d.i.b. at the top of each log was estimated by interpolation based on disk d.i.b. measurements. Lumber widths cut from a log were calculated assuming the maximum width cant would be cut from a log based on the following log scaling diameter requirements to produce dimension lumber of a specific width:

Dimension lumber size (inches)	Minimum log scaling diameter (inches)
2 by 4	5.0
2 by 6	6.1
2 by 8	8.0
2 by10	10.0

Average lumber grade yields per log were estimated based on log scaling diameter, log length, and log grade of the felled trees, then expanded to per acre yield based on measurement plot tree tallies. Standing tree stumpage price per acre was estimated using the following stumpage values based on Timber-Mart South (2006):

Pulpwood: 5.0 to 7.9 inches d.b.h. at $6.00 per green ton
Chipping-saw: > 7.9 and < 12.0 inches d.b.h. at $22.00 per green ton
Sawtimber: ≥ 12.0 d.b.h. at $38.00 per green ton.

Wholesale lumber value (WLV) based on mill tally was calculated using estimated lumber volume by grade, width and length and Random Length prices for January 17, 2007 (Random Length, 2007).

Breakeven stumpage, the maximum a manufacturer can pay for standing stumpage when considering costs and revenue, was estimated using the following equation:

$$BESTUM = (WLV + CHIPS + BKRES) - (CUTHALL + MANFACT + IRR) \quad (1)$$

where:

BESTUM = break-even stumpage, dollars per ton
WLV = wholesale lumber value, dollars per thousand board feet
CHIPS = wood chips, assume worth $22.00 per ton
BKRES = bark residue, assume worth $14.00 per ton
CUTHAUL = cut and haul costs, assume $16.50 per ton
MANFACT = manufacturing costs, assume $110 per thousand board feet
IRR = internal rate of return, assume 18 percent

RESULTS

Initial spacing at planting had a profound effect on average d.b.h., THT and number of surviving trees per acre at age 21 (table 1). Average d.b.h. and THT increased with increased spacing or decreasing number of trees per acre. The trees planted at 6 by 8-feet spacing averaged 7.7-inches d.b.h. and a 72-foot height, compared to trees planted at 12 by 12 spacing, which averaged 11.0-inches d.b.h. and an 81-foot height at age 21. The distribution of trees by d.b.h. class was influenced by spacing (fig.1). Increased spacing shifted the distribution of trees to the right into larger diameter classes. The closest spacing (6 by 8-feet) resulted in a large proportion of pulpwood size trees and few chipping-saw trees compared to the widest spacing (12 by 12-feet), which resulted in few pulpwood trees and nearly all chipping-saw and sawtimber trees at age 21. The number of chipping-saw and sawtimber trees increased from 265 trees per acre for the 6 by 8-feet spacing to 340 trees per acre for the 6 by 12-feet spacing and decreased to 254 trees per acre for the 12 by 12-feet spacing (table 1). The proportion of trees surviving at age 21 ranged from 65 percent for the 6 by 8-feet spacing to 90 percent for the 10 by 12- and by 12-feet spacing.

The average number of knots on the stem to a 4-inch d.o.b. top increased with increase in spacing and averaged 60 for the 6 by 8-feet spacing compared to 81 for the 12 by 12-feet spacing (table 2). Average knot diameter increased only slightly with increased spacing, ranging from 1.3 inches for the 6 by 8-feet spacing to 1.5 inches for the by 12 by 12-feet spacing. However, average maximum knot diameter increased from 2.7 and 2.6 inches for the 6 by 8- and 6 by 10-feet spacing, respectively, to 3.1 inches for the 12 by 12-feet spacing. Knot diameter within the row and between the rows did not appear to differ. For example, average knot diameter for the rectangular spacing of 6 by 12-feet was 1.3 inches within the row compared to 1.4 inches between the rows.

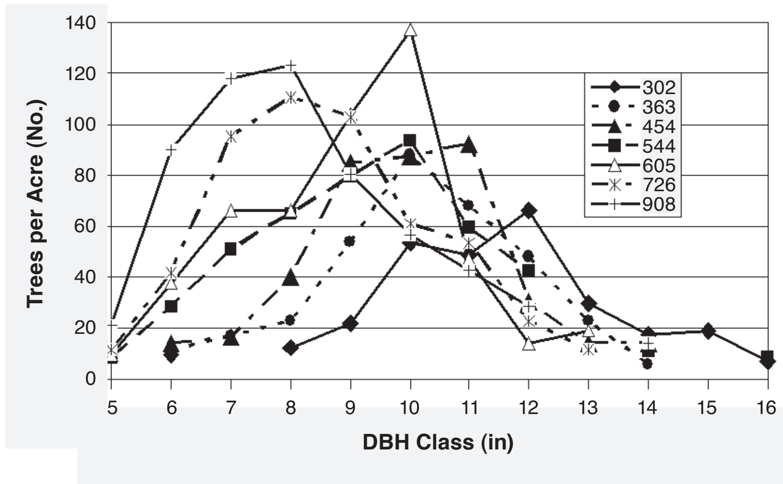

Figure 1—Effect of initial spacing on average diameter distribution of loblolly pine trees at age 21.

At age 21 average total heights of the felled trees ≥ 8 inches d.b.h. varied only slightly with increased spacing, averaging 82 feet for the 6 by 8-feet spacing compared to 85 feet for the 8 by 12- and 10 by 12-feet spacing (table 2). Average sawlog merchantable height to a 5.5-inch d.o.b. top, however, increased with increased spacing and averaged 2.5 logs for the 6 by 8-, 6 by 10-, 6 by 12-, and 8 by 10-feet spacing compared to 3.0 logs for the spacings of 8 by 12-, 10 by 12- and 12 by 12-feet. The primary reason for the change in sawlog merchantable height is that the rate of stem taper decreased with an increased spacing. Average form class was 75 for spacings of 6 by 8-, 6 by 10-, and 8 by 10-feet spacing, increasing to 77 for the 8 by 12-feet spacing, and decreased to 76 for the10 by 12- and 12 by 12-feet spacing (table 2).

Average total stem green weight per acre with bark to a 3-inch d.o.b. was estimated to be 190 tons for the 6 by 8-feet spacing and increased to 215 tons for the 8 by 10-feet spacing and then decreased to 195 tons for the 12 by 12-feet spacing (table 3). Green weight per acre of chipping-saw and sawtimber to a 5.5-inch d.o.b. top was estimated to increase from 114 tons for the 6 by 8-feet spacing to 180 tons for the 8 by12-feet spacing and then decreased to 178 tons for the 12 by 12-feet spacing (table 3). The weight per acre of pulpwood trees to a 3-inch top and the weight of pulpwood in the tops of chipping-saw and sawtimber per acre decreased as spacing increased. When pulpwood and pulp tops are priced at $6 per ton, and all trees ≥ 8-inches d.b.h. are priced as chipping-saw at $21/ton, total standing tree stumpage was highest for the 8 by 12-feet spacing ($3,979 per acre) and lowest for the 6 by 8-feet spacing ($2,763 per acre) (table 3). When chipping-saw was defined as trees 8.0 to 11.9 inches and priced at $21/ton, and sawtimber was defined as trees ≥ 12.0 inches and priced at $38/ton (Timber Mart-South 2006), the 12 by 12-feet spacing had the highest stumpage at age 21 while the lowest stumpage occurred at the 6 by 8-feet spacing (table 3).

When marketing southern pine dimension lumber, width, length, and grade all are important in determining wholesale lumber value. Figure 2 shows the number of sawlogs per acre based on scaling diameter that would be harvested from each spacing, assuming all trees ≥ 8-inches d.b.h. were

Table 2—Average tree[1] and knot characteristics for sample trees by initial spacing

	Spacing (feet) / TPA (no.)						
Variable	6X8 908	6X10 726	6X12 605	8X10 544	8X12 454	10-X12 363	12X12 302
Number of trees sampled (no)	20	21	14	19	20	14	21
d.b.h. (inches)	9.7	9.7	9.7	10.1	10.3	10.8	11.7
Total height (feet)	82	83	83	83	85	85	84
Sawlog merchantable height to 5.5-in d.o.b. (feet)	42	43	42	44	48	49	51
Stem form class	75	75	75	75	77	76	76
Average height to base live crown (feet)	57	59	56	58	59	58	56
Avg number of knots in stem to 4.0 inch d.o.b. top (No.)	60	64	65	72	76	69	81
Average diameter of knots (inch)	1.3	1.4	1.4	1.5	1.4	1.5	1.5
Average maximum diameter of knots (inch)	2.7	2.6	2.8	3.0	3.0	3.0	3.1

[1] Trees ≥ 8.0 inches d.b.h.

Table 3— Average stand characteristics by initial spacing for unthinned loblolly pine at age 21

Variable	Spacing (feet) / Trees per acre (no.)						
	6X8	6X10	6X12	8X10	8X12	10X12	12X12
	908	726	605	544	454	363	302
Basal area (square feet per acre)	199	202	218	216	207	189	187
Total stem weight to 3-inch d.o.b. (tons per acre)	190	195	213	215	214	196	195
Weight pulpwood trees < 8.0-inch d.b.h. (tons per acre)	56	48	31	26	11	7	5
Chip-Saw weight to 5.5-inch d.o.b. (tons per acre)	114	126	158	168	180	170	178
Weight of topwood 5.5- to 3.0-inch d.o.b. (tons per acre)	20	21	24	21	23	19	14
Stumpage[1] pulpwood trees and tops ($ per acre)	652	661	627	536	474	383	272
Stumpage pulp + trees ≥ 8.0 inch ($ per acre)	2,763	3,069	3,652	3,809	3,979	3,737	3,838
Stumpage pulp + chip-saw + sawtimber ($ per acre)	3,107	3,243	3,952	4,444	4,411	4,445	5,294
Breakeven stumpage trees ≥ 8.0 inch ($ per acre)	2,667	2,946	3,482	3,572	3,724	3,466	3,486
Lumber volume (mill tally) (1000 boardfeet per acre)	28.7	28.8	35.3	34.8	41.7	34.6	39.1
Wholesale lumber value ($ per acre)	8,628	8,648	10,658	10,745	12,995	10,676	12,763

[1] Stumpage prices

Pulp = $6 per ton

Chip-saw (trees 8.0- to 11.9-inch d.b.h.) = $21 per ton

Sawtimber Trees ≥ 12.0-inch d.b.h. = $38 per ton

Breakeven stumpage is maximum price per ton buyer can pay and covers costs and internal rates of return as shown in figure 3.

harvested and processed into a maximum number of 16 foot sawlogs plus 8-foot top logs when needed to a 5.0-inch d.i.b. top. The number of sawlogs with a scaling diameter sufficient to make 2 by 4 and 2 by 6 lumber, but not large enough to make 2 by 8-lumber, was highest in the closer spacings and lowest in the wider spacings. The number of sawlogs of sufficient diameter to produce 2 by 8-lumber was lowest for the closer spacings and increased with increased spacing (table 2). Only at the widest spacings (10 by 12- and 12 by 12-feet) would more than 20 sawlogs be harvested at age 21 that are large enough to produce 2 by 10 lumber and 2 by 12 lumber (figure 2).

The 8 by 12-feet spacing produced the highest lumber volume per acre mill tally, based on sawlog scaling diameter, length and log grade, followed by the 12 by 12-feet spacing, while the lowest lumber volume per acre occurred for the 6 by 8-feet spacing (table 3). Based on lumber prices for January 2007 (Random Length, 2007) the 8 by 12-feet spacing also yielded the highest wholesale lumber value per acre followed closely by the 12 by 12-feet spacing. Sawlogs from the 12 by 12-feet spacing were, on average, larger in scaling diameter (7.3 inches) than those from the 8 by 12-feet spacing (6.8-inches). However, the 8 by 12-feet spacing produced 231 more sawlogs per acre than the 12 by 12-feet spacing. The 6 by 8-feet spacing had the lowest lumber value per acre and the smallest average log scaling diameter (6.2 inches).

Figure 3 shows the average breakeven stumpage price per ton by d.b.h. class for a simulated harvest of this spacing study

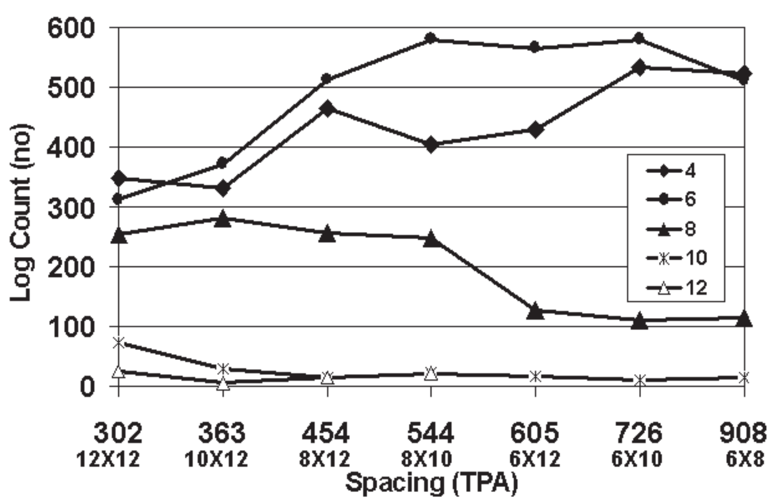

Figure 2—Effect of initial spacing on average number of sawlogs by lumber cant width for loblolly pine at age 21.

at age 21 based on equation (1). Breakeven stumpage was lowest for 8-inch trees ($18 per ton) and ranged from $21 to $23 per ton for trees 9 to 14 inches d.b.h. Breakeven stumpage jumped from a chipping-saw price of about $22 per ton to a sawtimber price of $32 -$36 per ton for trees 15-inches d.b.h. and larger (fig. 3), not 12-inches d.b.h. as indicated by Timber Mart-South (2006) market average prices. The reason for this difference in initial sawtimber pricing is that Timber Mart-South prices are based on the average market price of significantly older trees that have a larger volume of clear wood in the lower bole, resulting in higher log grades and thus a larger volume of high grade lumber. Based on breakeven stumpage prices, the 8 by 12-feet spacing would bring the highest stumpage per acre ($3,724) followed by the 8 by 10-feet spacing ($3,572). The 12 by 12-feet spacing would bring an estimated $ 3,486 per acre at age 21.

CONCLUSIONS

Initial spacing has a large impact on tree survival. Only 65 percent of the trees planted at 6 by 8feet were surviving at age 21 compared to 90 percent survival for the trees planted at 10 by 12 and 12 by 12 feet. Average number of knots, average knot diameter, and average maximum knot diameter increased with increased spacing. The average diameter of knots within the row and between rows did not vary greatly. Average sawlog merchantable height increased with increased spacing and averaged 2.5 logs for the 6 by 8-, 6 by 10-, 6 by 12-, and 8 by 10-spacing compared to 3.0 logs for the 8 by 12-, 10 by 12- and 12 by 12-feet spacing. Wood and bark total stem green weight per acre to a 3-inch d.o.b. top was highest in the 6 by 12-, 8 by 10- and 8 by 12-feet spacings. When chipping-saw is defined as trees 8.0 to 11.9 inches and priced at $21/ton, and sawtimber is defined as trees ≥ 12.0 inches and priced at $38/ton, the spacing with the highest stumpage at age 21 is 12 by 12-feet. However, when break-even stumpage price per acre for a 21-year-old stand are used, the 8 by 12-feet spacing has the highest stumpage. Estimated volume of lumber per acre was slightly higher for trees planted at 8 by 12-feet spacing compared to that for trees planted at the12 by 12-feet spacing, and lowest for trees planted at 6 by 8-feet.

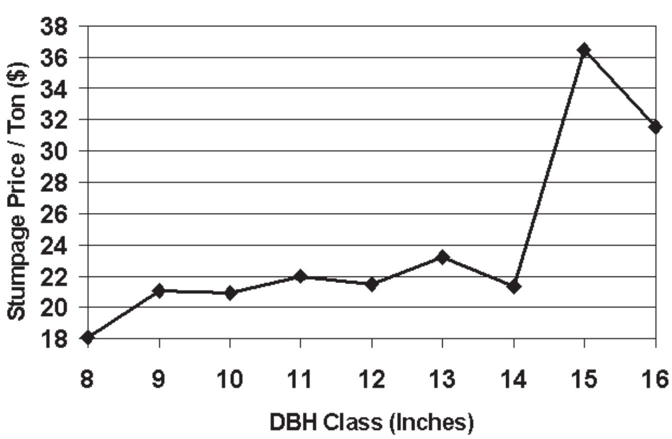

Figure 3—Average break-even stumpage by d.b.h. class for loblolly pine at age 21.

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THE DENSEST LOBLOLLY PINE STAND AND ITS SILVICULTURAL IMPLICATIONS

Boris Zeide and John Stephens[1]

Abstract—Estimation of stand density index has been based on the assumption that the only cause of mortality in fully stocked stands is diameter growth. For example, when average diameter increases by 1 percent, a fixed proportion (1.6 percent) of trees must die, regardless of age, average tree size, and other factors. This balance between growth and mortality entails the maximum limit of density index; for loblolly pine it is 1,140. We found a 10-year-old loblolly pine stand with density that is up to 59 percent greater than the maximum. The decisive factor of this exceptional density is the abundance of seeds shed by a row of mature pines. This finding requires reconsidering our understanding of stand dynamics. It is likely that, in addition to diameter growth, some internal factors contribute to mortality of trees. The proportion of mortality is not fixed but may change with age. Besides theoretical implications, further analysis of the reported finding can produce better methods of density estimation.

INTRODUCTION

Growth and yield of forest stands depend on climate, site quality, tree species, age, competition control, stand density, rotation age, and other factors. There are two reasons why stand density occupies a special place among these factors. First, it is one of the most influential variables for predicting tree form, growth, and survival. In dense stands mature trees can be twice as tall but a third as thick as their open-grown conspecifics of the same age. Second, unlike climate and site quality, density can be controlled easily and often profitably. Therefore, control of density has been a major tool of forestry from its beginning.

MEASURING STAND DENSITY

To control density we need to know how to measure it. We still do not have a reasonable and widely accepted definition of density. The proximity of trees and branches, their size and arrangement, distribution of foliage, form and depth of roots—all these and many other factors bear on stand density. Usually, density is characterized by fittingly vague adjectives such as "dense" or "understocked."

Unlike ecologists who use number of organisms per unit area as measure of density, foresters have intuited the idea that, in addition to the number, stand density depends on tree size. Reineke's (1933) stand density index, the most reasonable, though not most common measure of density, uses both tree size and their number. It is based on the reciprocal relationship between average diameter, *D*, and number of trees per unit area, N_n, in fully stocked (normal) stands:

$$N_n = kD^{-r} \qquad (1)$$

where *k* and *r* are parameters. Reineke believed that parameter r = 1.605 is constant for all species and locations. This equation says that a certain increase in average diameter, *dD*/*D*, eliminates a fixed proportion of trees equal to *r dD*/*D*.

Reineke realized that the relationship between number of trees and diameter in fully stocked even-aged stands can be used as a standard for estimating density in stands of any degree of stocking. In the stand density index, *SDI*, that he proposed:

$$SDI = N\left(\frac{D}{25}\right)^r \qquad (2)$$

the number of trees, *N*, needs not to be normal, as indicated by the absence of the subscript *n*, but parameter *r* must be found in normal stands. Stand density index has a clear meaning: it is the number of trees per unit area with a specified diameter of 25 cm in metric and slightly larger in English units (10 inches = 25.4 cm).

Faults of other measures of density are either poor choice of opposites or their inappropriate combination. The most popular measure of stand density, basal area of trees per unit area, has the same components as Reineke's index (number of trees and stem diameter). The difference is in the power of diameter: it is 2 for basal area and 1.6 for the index. As a result of this difference, basal area varies in equally dense stands. Thus, according to a well known density guide (Gingrich 1967) adopted as the U.S. Forest Service standard for stocking guides, when average diameter is 10 cm, a stand is fully stocked if its basal area reaches 11 m^2/ha. However, for a stand with diameter 40 cm, basal area should be 60 percent greater than 11 m^2/ha to qualify for the same full stocking. And conversely, the same basal area can be found in stands differing in stocking. Gingrich's guide considers a stand with a basal area of 17 m^2/ha understocked when the average diameter is greater than 38 cm. When the diameter is less than 8 cm, the stand with the same basal area is classified as overstocked. For the intermediate diameters, it is fully stocked.

Maximum Level of Density

The balance between growth and mortality in fully-stocked stands suggests the existence of maximum stand density index common to all stands of a given species, regardless of

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site quality, age, and tree size. Site quality or planting density may affect the time of reaching the maximum but not its value. Due to local disturbances caused by mortality of single trees, even in densest stands actual indices are always below the maximum. To establish a perfect maximum, Reineke (1933) drew a line above the cloud of points representing average diameters and numbers of trees in the fully stocked stands. The maximum he reported for loblolly pine was 450 in English units. In metric units, we use 25 cm instead of 25.4 (= 10 inches) as the basis. Since Reineke (1933) did not provide any justification for his highly precise value of *r* (= 1.605), it is commonly rounded to 1.6 (contrary to Reineke's belief, this value varies with the shade tolerance of a species). With these modifications in metric units the maximum per hectare is 1140 (= 450*2.471* (25.4/25) ^1.6). This density is about 60 percent greater than average (normal) density of 700 for his plots.

PERFECTING REINEKE'S INDEX

Reineke's index is the best available measure of stand density because, unlike basal area, it does not confuse understocked stands with overstocked ones. Still, many researchers reported that number of trees drops faster than the power function of diameter (Zeide 2005). For this reason, Meyer (1938) used a curved-down (on the log-log scale) line to relate number and diameter of dense stands. Also it was found that *r* changes with age, being smaller in younger stands. In young (average age of 20 years) loblolly pine stands, Williams (1994) found $r = 1.5$. In older stands (from 19 to 77 years) of the same species in the same region (northern Louisiana), Meyer (1942) came up with the value of 1.9. These discrepancies suggest that, along with tree size, there are other nonrandom factors of tree mortality.

Internal Factors of Tree Mortality

Reineke's equation is built on the assumption that trees die as a result of single physical process: the increase in size of neighboring trees. The equation disregards internal physiological and morphological processes such as diminishing tolerance to shading, senescence, and impediments associated with increasing tree size. We know that younger trees generally tolerate deeper shade than older ones and that in mature stands age gap area becomes more pronounced. Since seed production increases with age and tree size, it is of selective advantage for older trees not to choke their progeny, but to loosen the canopy and let light in for advance regeneration. This knowledge should help us to design a better size-number relationship and improve density estimates.

Aging, diminishing tolerance, and other internal factors work in the same direction of continuously reducing tree vigor. Since stand density index denotes number of trees with diameter 25 cm, if they exist, internal factors would make the maximum (1,140) smaller in older stands with diameter greater than 25 cm, and larger than 1,140 in younger stands. These manifestations of internal factors can be tested experimentally.

Gap Accumulation in Older Stands

To account for aging, it was proposed to add to Reineke's equation a module describing diminishing canopy cover (Zeide 2005). Observations that the number of trees falls faster than the power function suggest the exponential form of the module. Because diminishing cover is associated with increasing age and tree size, either of these variables could be used to derive the module of canopy cover. The augmented relationship between number of trees, N_n, and average diameter in fully stocked stands can be written as:

$$N_n = a\left(\frac{D}{25}\right)^{-b} e^{\frac{25-D}{c}} \tag{3}$$

where *a* is normal stand density, *b* is the rate of tree mortality caused by the increase in crown size, and *c* is the parameter of mortality due to diminishing canopy cover. The resulting model accounts for the two factors of tree survival (or mortality): increase of tree size and accumulation of gaps particularly evident in older stands. This equation does not impose canopy gaps. If canopy cover is complete, *c* would tend to infinity and the equation would be reduced to Reineke's.

Equation 3 uncovers two components that are conflated in Reineke's equation. First is the effect of physical expansion of tree crown; its rate is $b < r$. The second component of tree mortality is caused by internal factors; it is described by the exponential module. For medium values of diameter, the combination of both components can be approximated by a power function with parameter *r*. The difference between Reineke's equation and equation 3 becomes more pronounced at the edges of diameter-number relationship.

Tenacity of Young Trees

According to Reineke's equation, when diameter increases by factor $p > 1$, the fixed $(1 - p^{-r})$ proportion of trees must die, regardless of age, tree size, and other factors. This assumption does not agree with observations that younger trees can tolerate deeper shade. They are more tenacious than older ones. Since this age-related persistence is not accounted by Reineke's equation, we may expect deviations from the maximum density he reported. The action of internal factors can be manifested not only in a lower maximum in older stands but also in a greater maximum in young stands when initial number of trees is sufficiently high. This conclusion offers a simple way to confirm (or reject) the hypothesis that the proportion of trees dying in response to the same increase in diameter increases with age and tree size. If the hypothesis is correct, it should be possible to find young stands with a higher density index than Reineke's maximum of 1,140.

The hypothesis that initial number of trees may affect stand density index is not new. It was tested and rejected by Shouzheng and others (1995). They found that maximum density index is not significantly influenced by initial stand densities. On the other hand, VanderSchaaf (2006) showed that maximum density index depends on the time when trees close their canopies and competition begins. The index is higher for stands with larger initial number of trees because they start competing earlier.

DOCUMENTING THE HIGHEST STAND DENSITY INDEX

The arguments presented above suggest that the younger the stand, the higher the maximum of density should be. The highest maximum is the earliest one. The maximum is limited by initial number of trees and seed supply because these limitations postpone the age and the level of the maximum. An ideal method to document the highest maximum is to grow seedlings in a nursery until density index culminates. The next best and quicker option is to locate young stands with plentiful regeneration.

Stand Description

A tract of land, half a kilometer north of the Arkansas University School of Forestry, was clearcut in 1996 and planted 2.4 by 2.4 m (8 by 8 feet) with 1-year-old loblolly pine in February 1997. The ground was not prepared well and ten years later, about half of planted pines survived, interspersed with much hardwood ingrowth. The situation differed on the eastern side of the tract where a single row of mature pines, growing 10 to 15 m apart, bounds the stand. The pines are 30 to 60 cm in diameter and were not cut because they belong to a different owner. These pines heavily seeded the plantation where the soil was scarified by cutting and planting.

By 2006, the portion of the plantation adjacent to the row of pines was exceptionally dense. This strip, 15 to 25 m wide and 400 m long, starts at the edge of the crown projections of seed pines. It was composed of planted 10-year-old (from seed) trees and numerous pine volunteers with a few tiny hardwoods (< 1 percent by basal area). While the diameter of planted trees was 9 to 12 cm, the diameter of 9 year old volunteers was 6 to 8 cm; 8 year olds were still smaller. Dead trees were 3- to 5-years-old and mostly smaller than 3 cm in diameter. The average age of live pines, including planted and natural regeneration, was 9 years.

Besides the combination of soil scarification and abundant seed source, there is nothing unusual about the stand. It is situated in the midst of the loblolly pine region, on flat ground, and has a typical site index of 65 (base age 25 years). Soil analysis (pH, nitrogen, phosphorus, potassium, and carbon) did not reveal any irregularities.

Density Profile

To document the extent of the dense strip, five point sampling transects were run with a BAF 4 (metric) prism starting from seed trees. Each transect was 100 m long and ran directly west perpendicular to the strip around the areas where the plots were established. Basal area was estimated every 10 m. Also the distance to the end of crown projection and distance to the end of dense regeneration were noted.

These measurements showed that the average distance from the seed trees to the end of crown projection (half of crown width) was 5.6 m; the distance to the end of dense regeneration was 24.5 m. Average results of five point sampling transects demonstrate that at the beginning, under the canopy of the seed trees, basal area is approximately 25 m^2/ha (fig. 1). By 10 m the basal area has increased to 37 m^2/ha and at 20 m is nearly 40 m^2/ha on average. At 30 m basal area drops back to 25 m^2/ha. By this point, the area of dense regeneration has ended. At greater distances, basal area stays at about 20 to 25 m^2/ha.

Plot Measurements

On the dense strip, eight square plots were established and measured in January-February of 2006 and another one in January of 2007 when the original plots were remeasured. The area of each plot is 25 m^2. Since we are interested in maximum and not average values, the plots are located in the middle of the dense strip with buffer zones, 4 to 6 m wide, of approximately equal density on both sides. Plots 1 through 5 are contiguous and oriented on a north/south bearing. Plots 3.1 and 3.2 are contiguous, perpendicular to, and directly to the west of plot 3. Plots 6 and 6.1 are located 70 m south from plots 1 through 5 and oriented directly to the north and south. In addition to diameter at breast height of all trees, total tree height, height to live crown, and crown width (at two perpendicular directions) were measured on a sample including all tree sizes. The position of each tree on the densest plot 1 was mapped.

RESULTS

The results of plot measurements show that, given sufficient regeneration, Reineke's maximum can be exceeded by as much as 59 percent (table 1). We have not seen references

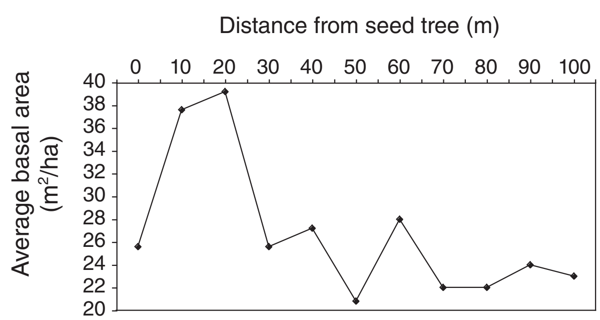

Figure 1—Average basal areas of five transects at 10 m intervals from seed trees.

Table 1—Characteristics of loblolly pine plots measured in 2006 and 2007

PN	Age	D	N	BA	SDI	Ratio
1	9	4.89	24400	45.82	1792.8	1.57
	10	5.37	21200	48.04	1810.6	1.59
2	9	4.82	22000	40.12	1579.1	1.39
	10	5.13	20400	42.17	1618.5	1.42
3	9	5	22000	43.2	1675.4	1.47
	10	5.31	20800	45.98	1741.4	1.53
3.1	9	6.23	12400	37.78	1341.9	1.18
	10	6.6	11600	39.66	1376.5	1.21
3.2	9	6.18	13600	40.84	1454.8	1.28
	10	6.73	12400	44.14	1519.7	1.33
4	9	5.13	15200	31.4	1205.4	1.06
	10	5.47	15200	35.68	1335.2	1.17
5	9	6.34	12400	39.09	1379	1.21
	10	6.81	12400	45.12	1546.8	1.36
6	9	4.74	22400	39.55	1566.6	1.37
	10	5.28	21600	47.33	1795.6	1.58
6.1	10	5.4	18000	41.28	1552	1.36

PN=plot number; Age=age in years; D=quadratic mean diameter in cm; N=number of trees per hectare; BA=basal area in m^2/ha; SDI=stand density index; Ratio is ratio of SDI and Reineke's maximum of 1,140.

to so high a stand density index in literature. Out of 4 885 FIA plots, 12 have indices higher than Reineke's maximum with the highest being 1,384. Since the index has increased on all the plots from 9 to 10 years, it has not yet reached the highest value.

DISCUSSION

The importance of stand density to forest management justifies continuing search for deeper understanding of density and better methods for its estimation. The finding of a stand with a substantially higher density index than the maximum established by Reineke (1933) suggests insufficiency of his equation. This finding indicates that some factors, other than physical expansion of tree sizes, are involved in the process of tree mortality. The reported discovery calls for a revision of existing methods for density estimation.

Most likely, these hypothetical factors are the internal physiological and morphological processes that detract from vitality as trees get older. Among these processes is diminishing tolerance to shading, and increasing tree size, which slow the growth by diverting resources to supporting structures and respiration. These factors contribute to tree mortality as is evident from the area of gaps, which becomes more pronounced with age.

The presented arguments suggest that the younger stand, the higher the maximum density. The highest maximum is the earliest one. The maximum is limited by initial number of trees and seed supply because these limitations postpone the age and the level of the maximum. These considerations provide suggestions for a model describing tree mortality. The model should use both external and internal factors for describing change in number of trees. In agreement with evidence, the predicted slope in the middle range of diameters should be around -1.6 as in Reineke's equation. Unlike this equation, this slope would be a combination of two or more processes. The model should predict maxima higher than Reineke's for younger stands and lower maxima for older stands.

ACKNOWLEDGMENTS

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PINE SEED TREE GROWTH AND YIELD ON THE CROSSETT EXPERIMENTAL FOREST

Don C. Bragg[1]

Abstract—In late 2002, three small tracts of loblolly (*Pinus taeda*) and shortleaf (*Pinus echinata*) pine on the Crossett Experimental Forest in Ashley County, AR, were cut using a seed tree method. Immediately after harvest, these cutting units averaged 7.7 stems and 13.8 square feet of pine basal area per acre. By 2006, live seed tree density dropped to 7.4 stems per acre, while basal area increased to 14.4 square feet per acre. Per acre residual sawtimber volumes initially averaged 2,076 board feet (Doyle) or 12.1 tons, increasing to 2,266 board feet (12.8 tons) after 3 full growing seasons. Due to an annual mortality rate of approximately 1.2 percent, net stand growth was low, averaging only 2.9 percent in board foot volume and 1.8 percent for sawtimber tonnage. However, individual seed trees fared noticeably better. For most, annual board foot growth ranged between 4 and 9 percent, and yearly sawtimber tonnage growth averaged between 3 and 6 percent. In general, small diameter seed trees added volume most rapidly and presented the lowest risk of mortality-based loss. Though modern harvesting techniques pose new challenges, seed tree management remains a viable alternative for mixed pine stands.

INTRODUCTION

Even though pine plantations are the fastest increasing forest type in the Southern United States, most regions are still dominated by naturally regenerated stands (Conner and Hartsell 2002). For landowners not interested in the relatively high impact treatments associated with plantations, seed tree harvests are an effective means to regenerate loblolly (*Pinus taeda*) and shortleaf (*Pinus echinata*) pine-dominated stands. Long-term observations have shown the efficacy of this technique in mixed pine forests in southern Arkansas and other regions (Cain and Shelton 2001a, Wahlenberg 1960, Williston 1987, Schultz 1997).

Over the years, most research on seed tree silviculture in loblolly and shortleaf pine forests has focused on ensuring pine regeneration (for example, Baker 1982, Grano 1949, Grano 1954, Lotti 1953). More than twenty years of experience on the Crossett Experimental Forest (CEF) has shown seed production in mature loblolly and shortleaf pine stands is rarely a limiting factor, with annual sound seed production averaging about 175,000 per acre (Cain and Shelton 2001b). Although there were some years that registered as unequivocal failures (less than 10,000 sound seeds per acre), 2-year cumulative totals during this period never fell below 100,000 sound pine seeds per acre, which is thought to be more than adequate to fully stock a properly prepared site (Cain and Shelton 2000, Cain and Shelton 2001b).

Given these decades of experience, it may seem that there is little worth studying in seed tree harvests of loblolly and shortleaf pine. However, only limited guidance has been provided on the growth, yield, and survivorship potential of the residual overstory following a seed tree harvest in this cover type. As with any silvicultural system dealing with a residual overstory, successful seed tree management involves balancing growth with the risk of loss. This paper focuses on the management of the residual trees, or overwood, using observations from a recent study of seed tree harvests.

METHODS

Study area

The Crossett Experimental Forest is located on the Upper West Gulf Coastal Plain in Ashley County, AR, approximately seven miles south of the city of Crossett and just north of the Louisiana state line. Slopes are < 5 percent across the entire forest and there are no permanent stream drainages. A thin loess cap covers most of the CEF and low, circular prairie mounds are common. Soils on the CEF fall into one of three main types: Arkabutla silt loams (Aeric Fluvaquents) along the ephemeral drainages; Providence silt loams (Typic Fragiudalfs) on the side slopes of the drainages; and Bude silt loams (Glossaquic Fragiudalfs) on the upland flats (Gill and others 1979, Shelton and Cain 1999). The three study sites were found on either Providence or Bude soils and are virtually level. Elevation of the CEF ranges from 125 to 135 feet above sea level, and the growing season is approximately 240 days, with an average annual precipitation of about 55 inches (Shelton and Cain 1999). Long-term climate records for the area show that there is no marked seasonality in precipitation, but it is not unusual to have dry periods in the late summer and fall, or wet winters and springs.

The presettlement upland forests of the region were largely old growth, with the composition being a relatively even mixture of loblolly and shortleaf pine and a scattering of hardwoods (Bragg 2002, Chapman 1913). The area that would eventually become the CEF was cleared of its virgin timber by the Hickory Grove Camp of the Crossett Lumber Company between 1915 and 1920 (Darling and Bragg 2008). The land then reseeded naturally over the next couple of decades, even though portions were repeatedly burned and heavily grazed until the property was leased to the Southern Forest Experiment Station in 1933 (Reynolds 1980). The CEF officially came into existence in 1934, and the stands were rehabilitated using a variety of low cost techniques. Over the years, the Forest Service acquired fee title to the property, and many of these stands have been managed and harvested for decades.

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The present day forests of the CEF are naturally regenerated stands of loblolly pine with a significant component of shortleaf pine. Management practices have kept hardwoods noticeably less common and largely restricted to areas along ephemeral streams, or occasionally in stands studied for mixed composition. For this study, the stands are managed exclusively for pine, and any hardwoods are eliminated when they start to compete with the pines. Pine seedling establishment is generally good to excellent on the CEF, especially when the logging activities clean the site and expose favorable mineral substrates. Competition from graminoids, forbs, vines, briars, shrubs, and hardwood trees can be intense on these relatively fertile sites, and the window of opportunity for good pine establishment rarely exceeds more than one or two growing seasons (Wahlenberg 1960, Williston 1987).

Silvicultural Treatments

The three parcels of interest were logged in November of 2002. Prior to harvest, these mature, even-aged pine stands had been thinned repeatedly. Generally similar in structure, composition, site, and age prior to their seed tree harvests, these stands were part of two different studies (fig. 1). The Block and Strip parcel (hereafter, B&S, 5.0 acres in size) is part of a demonstration on the potential of naturally regenerated pine stands to produce large quantities of timber over relatively short time periods. The other two tracts (hereafter, MOC1 and MOC2, both 4.4 acres in size) were replicates in a study of cutting methods, which is a long-term comparison of the productivity of different regeneration techniques (Cain and Shelton 2001a). Each stand was harvested using a conventional seed tree approach for loblolly and shortleaf pine forests. On average, parcels were cut to a residual density of 7.7 trees per acre and 13.8 square feet per acre of basal area.

Measurements and Analysis

Annual inventories have been conducted of each seed tree cut starting in spring 2003 and continuing every year to 2006. During these cruises, each pine seed tree was checked to see if it was still alive. Live trees had their diameter at breast height (d.b.h.) measured to the nearest 0.1 inch with a steel diameter tape. Pines that died were flagged in the records as deceased, and then no longer tracked. Because the focus of this project was on overwood growth, yield, and survivorship, no effort was made to track seed production. In the spring of 2006, increment cores were taken at d.b.h. from a sample of 7 to 10 seed trees from each stand spanning the range of diameters and, presumably, will approximate the current age structure of the parcels.

Individual tree volume estimates were produced using the following local formula (Farrar and others 1984):

$$V_D = 170.10568 - 37.68584\,d.b.h. + 2.34851\,d.b.h.^2 \quad [1]$$

where V_D is the board foot volume (Doyle rule). Since no height data were available at the time of the measurement, pine sawtimber weight estimates were derived by first using:

$$V_C = -92.48602 + 20.01464\,d.b.h. - 1.58044\,d.b.h.^2 + 0.06591\,d.b.h.^3 - 0.00088\,d.b.h.^4 \quad [2]$$

where V_C is the sawtimber cubic foot volume (Farrar and others 1984). Each cubic foot of pine sawtimber was assumed to weigh 64 pounds (green weight; Patterson and others 2004), so sawtimber tonnage was calculated as: (V_C × 64) / 2000. Per acre estimates of board foot volume and tonnage were arrived at by summing all values by parcel, and then dividing by the cutting unit acreage. Individual tree growth rates were also expressed as a percent. From the annualized percent growth increment for board foot volume, an exponential decay regression model was fit to generalize growth expectations of individual seed trees, using initial bole diameter as the independent variable.

Since the seed trees were chosen without regard to statistical design, it is inappropriate to make comparisons of significance between response variables. For example, even though both loblolly and shortleaf pines were retained as seed trees, contrasting differences in their growth rates would not be appropriate because there was no attempt to control for other sources of variation in their selection. All results will be discussed as case studies, since there were no other companion treatments using some other regeneration technique for comparison.

RESULTS AND DISCUSSION

Tree Size and Age

The somewhat older stands (average of 56 years, with some seed trees up to 70 years old) in this study had an average tree size of 285 board feet Doyle (including some stems over 500 board feet) (fig. 2). Not surprisingly, leaving almost eight seed trees per acre of this size guaranteed that relatively high volumes would be retained. In fact, given the size and age of the overstory of these treatment areas, the cutting units contained almost twice the residual volume as we conventionally recommend.

Stand Stocking and Mortality Patterns

In the spring of 2003, basal area averaged 13.8 square feet per acre across the three stands. Three years later, overwood pine basal area had increased to 14.4 square feet per acre (table 1). The gain came from seed tree basal area growth, not the recruitment of new trees. Stocking actually decreased slightly, with seed tree density dropping from 7.7 to 7.4 trees per acre during the same period, or an average annual seed tree mortality of about 1.2 percent. After three full growing seasons, mortality varied between stands, ranging from 0 percent to 8.1 percent of the initial seed tree number, with individuals succumbing to causes such as logging damage, lightning, and insects.

Over enough time, all of these sites will experience at least some mortality. However, given this low rate, there is little to be concerned about regarding long-term sustainability. During the observation period, no stand lost more than 3 total seed trees, and the highest annual mortality rate for any given cutting unit (MOC2) did not exceed 2.8 percent of the initial number of seed trees. At this rate, almost half the overwood would still remain 20 years after the regeneration harvest, and assuming a conservative growth rate of 3 percent per year and no salvage of dead seed trees, more than enough sawtimber should remain to provide for an operable cut. Even though individualistic mortality of seed

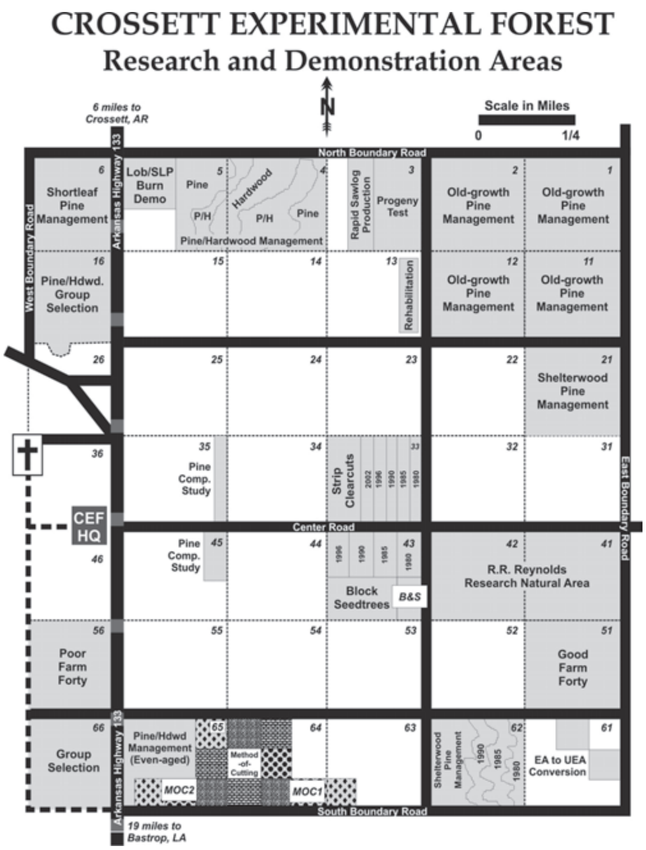

Figure 1—Map of the Crossett Experimental Forest in extreme southern Arkansas, with the three cutting units (B&S, MOC1, and MOC2) identified by italicized text.

trees is not a major problem, a catastrophic event—a severe windstorm, perhaps, could topple the exposed pines en masse and seriously impact the overwood.

Overwood Growth and Yield Performance

Per acre residual sawtimber yield averaged 2,076 board feet (Doyle) or 12.1 tons in 2003, increasing to 2,266 board feet or 12.8 tons, respectively, over the observation period (table 2). Individual cutting units produced anywhere from zero (or even slightly negative) net growth to as much as 165 board feet (0.70 tons, green weight) per acre per year, depending on growing conditions and the size of seed trees that died. However, on average, the cutting units added net growth of between 37 and 94 board feet per acre (0.12 to 0.38 tons per acre) per year during the observation period. This is somewhat less than the 148 board feet (0.8 tons) per acre per year reported in Cain and Shelton (2001a) for seed tree cuts on the CEF, but those stands were cut to 13 seed trees per acre. In contrast, fully stocked stands of approximately the same preharvest age (about 50 years) on similar sites produce about 400 to 600 board feet (2.1 to 2.6 tons of sawtimber per acre) per year (Cain and Shelton 2001a). While the understocked stands left after these seed tree cuts cannot be expected to perform like fully stocked stands, net growth was still positive. Furthermore, the yield of these stands was decidedly lower than its potential due to mortality losses, so stand-level realized growth averaged only 2.9 percent for board foot volume and 1.8 percent for sawtimber tonnage. However, most surviving seed trees fared noticeably better. For most, annual board foot Doyle growth ranged between 4 and 9 percent, and annual sawtimber tonnage growth averaged between 3 and 6 percent.

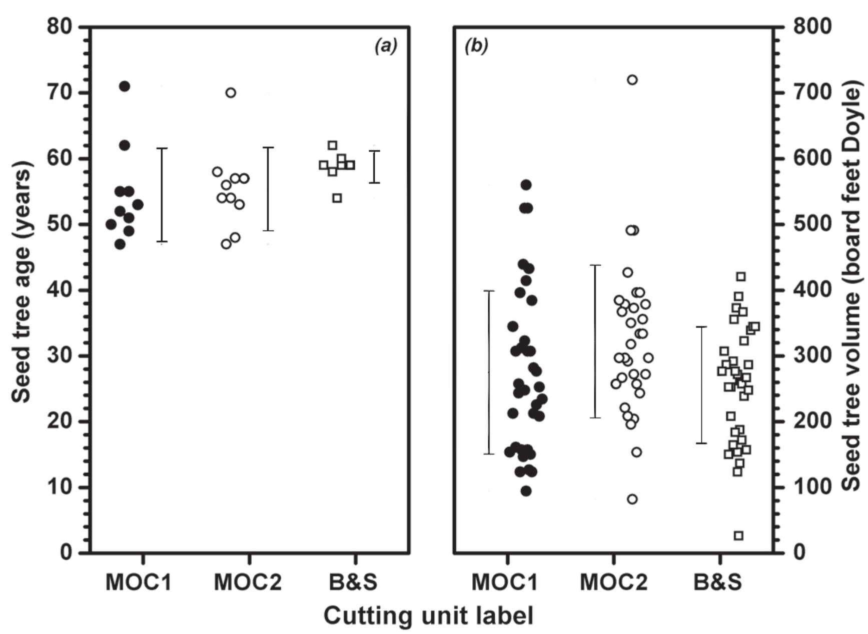

Figure 2—Sample seed tree age distribution by cutting unit (a) and range of initial tree board foot volumes for all pine seed trees (b) for this study on the Crossett Experimental Forest. The bars alongside each set of points represents plus or minus 1 standard deviation around the mean. Cutting unit labels follow discussion in text.

Table 1—Basic statistics of seed tree cutting units following regeneration harvest in November of 2002 (all measurements taken in the late spring of each year)

		Cutting unit				
Variable	Year	Block & Strip	Methods-of-cut #1	Methods-of-cut #2	Average of stands	Standard deviation
Live seed trees		---------- number/unit ----------				
Loblolly pine in	2003	37	29	27	31.0	5.29
Shortleaf pine in	2003	0	8	6	4.7	4.16
Loblolly pine in	2006	34	29	26	29.7	4.04
Shortleaf pine in	2006	0	8	5	4.3	4.04
Live seed trees		---------- number/acre ----------				
	2003	7.4	8.3	7.4	7.7	0.53
	2004	7.2	8.3	7.2	7.6	0.65
	2005	7.0	8.3	7.0	7.4	0.78
	2006	6.8	8.3	7.0	7.4	0.84
Live seed tree basal area		---------- square feet/acre ----------				
	2003	12.0	14.6	14.7	13.8	1.51
	2004	12.0	14.8	14.7	13.8	1.57
	2005	12.1	15.3	14.5	14.0	1.67
	2006	12.1	15.8	15.2	14.4	2.01
Cumulative dead seed trees		---------- number/unit (% of initial) ----------				
	2003	0 (0.0)	0 (0.0)	0 (0.0)	0.0 (0.0)	0.00 (0.00)
	2004	1 (2.7)	0 (0.0)	1 (3.0)	0.7 (1.9)	0.58 (1.66)
	2005	2 (5.4)	0 (0.0)	2 (6.1)	1.3 (3.8)	1.15 (3.33)
	2006	3 (8.1)	0 (0.0)	2 (6.1)	1.7 (4.7)	1.53 (4.22)

Table 2—Growth and yield of the pine seed trees on the three cutting units of the Crossett Experimental Forest

	Measurement year				Growing season		
Cutting unit	2003	2004	2005	2006	1	2	3
	------------ Net sawtimber yield (board feet/acre)[a] ------------				-- Net growth (board feet/acre) --		
Block & Strip	1740	1763	1805	1825	23	42	20
Methods-of-Cut #1	2168	2220	2353	2449	52	133	96
Methods-of-Cut #2	2322	2358	2358	2524	36	0	165
Average	2076	2114	2172	2266	37	59	94
Standard deviation	301.7	311.6	317.9	383.4	14.5	67.9	72.5
	--------------- Net sawtimber yield (tons per acre) ---------------				-- Net growth (tons per acre) --		
Block & Strip	10.4	10.4	10.5	10.6	0.04	0.13	0.01
Methods-of-Cut #1	12.7	13.0	13.6	14.0	0.24	0.60	0.43
Methods-of-Cut #2	13.2	13.2	13.2	13.9	0.07	-0.08	0.70
Average	12.1	12.2	12.4	12.8	0.12	0.22	0.38
Standard deviation	1.50	1.56	1.64	1.94	0.105	0.344	0.348

[a] Board feet, using the Doyle log rule.

An exponential decay model predicting annualized percent-based growth rates in terms of board foot volume (Doyle) based on initial tree diameter behaves in an expected manner—small diameter trees added increment at a considerably greater rate than large diameter pines (fig. 3). At least some of the higher rate of growth is due to the ability of small pines to more efficiently exploit resources following a regeneration harvest. However, much of this trend is due to how the change in growth rates was expressed. Since there is a base log diameter threshold for sawtimber (in this case, trees greater than 9.5 inches d.b.h.), the sharp initial decline of an exponential decay model is appropriate. After all, when expressed in terms of percentages, any tree crossing the threshold from sub-sawtimber (yield of zero) to minimal sawtimber experiences an infinite increase. The model also behaves reasonably as tree size increases—growth percentages will decline, substantially at first, then more gradually, approaching but never falling below zero. Linear functions (unless fitted piecewise for certain portions of the size class range) that follow this same basic pattern will eventually show negative growth, which is impossible.

The fit index (a non-linear analog to R^2) indicates that initial tree diameter accounts for slightly less than half of the variation in the data. Although more data near the extremes of the regression would be helpful in defining the curve, both the 95 percent prediction and 95 percent confidence bands are relatively narrow (fig. 3), suggesting that the general trend is acceptable. Given the nature of this study, it is virtually impossible to explain the noise, although it likely arose, in part, to factors such as logging-related damage, genetic variation in growth potential between individual seed trees, and events that have happened since the regeneration harvest—hardly controllable circumstances. However, some of the noise in the growth data may also be attributable to variation in initial crown density, which can be silviculturally manipulated. Grano (1957) reported that post-harvest growth of seed trees was related to the fullness of their crowns, with the diameter growth of denser crowned pines approximately 25 percent higher than less foliated individuals. Hence, it is conventionally recommended

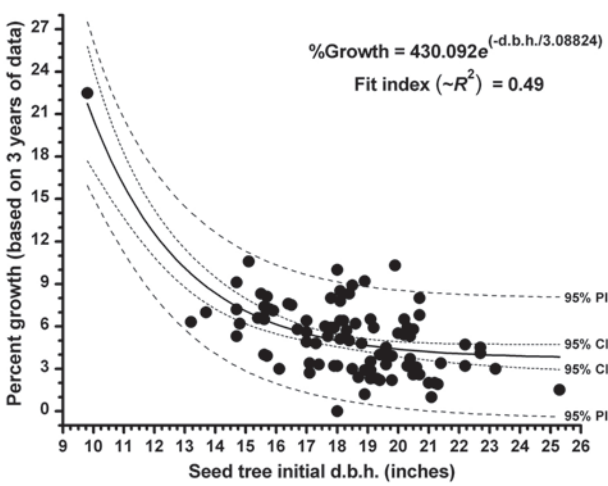

Figure 3—Annualized growth performance, measured as a percentage increase in board foot volume (Doyle) from initial d.b.h., for loblolly and shortleaf pine seed trees used in this study. 95 percent PI = 95 percent prediction interval, 95 percent CI = 95 percent confidence interval.

that pine stands to be regenerated with a seed tree cut be thinned several years prior to boost tree vigor and crown density. Unfortunately, no observations were made on crown density for the current study, making it impossible to verify if this contributed to any of the growth differences.

Overwood Silvicultural Lessons

Seed tree management provides many options for a landowner, depending on their silvicultural objectives, stand conditions, and site quality (Wahlenberg 1960). For a 40- to 45-year-old pine-dominated stand, we suggest landowners leave approximately 1,000 to 1,200 board feet (Doyle rule) per acre in quality seed trees (stems of at least 12 inches d.b.h. and of good form, with healthy crowns and abundant evidence of cones), and assume their volume can increase 6 to 8 percent per year. Hence, on a fairly typical site in southern AR and northern LA, the overwood will have increased to about 1,500 board feet per acre after 5 to 7 years (assuming no seed tree mortality). This level of cut is considered operable by most local logging crews, and should help to ensure that the overwood can be removed when desired.

It is possible to adjust the number and longevity of the seed trees following the regeneration harvest. For instance, in a 40- to 45-year-old stand, one can leave more overwood (perhaps starting at 1,500 board feet in 10 to 15 seed trees per acre) and then do a removal cut at three years. Under this circumstance, the landowner would want to be sure to cut the seed trees sooner, rather than later, because this quantity of overstory will likely provide too much competition with the pine regeneration as the new stand develops. In an older stand (for instance, more than 55 years) with larger seed trees, it is probably desirable to leave significantly fewer pines (as few as five or six per acre) to minimize how much timber value is risked in the overwood. This stand should also prove operable soon after the regeneration harvest, or can be left for considerably longer. However, I would caution against leaving too few seed trees, because attrition due to mortality is inevitable, and keeping at least some residual seed trees will greatly improve stand merchantability down the road.

Many foresters prefer early removal because it tends to minimize logging-related seedling mortality and the loss of economic value following to the death of seed trees. However, it is also possible to remove the overwood considerably later (12 to 20 years after the regeneration cut). In this study, the relatively large size of the seed trees (most are 90 to 100 feet tall) and their low density allows them to be retained for a long time. Unless clustered, the crowns of widely distributed seed trees are high enough above the forest floor so as to not provide serious competition for most of the younger trees. Even the loss of a limited amount of pine regeneration will have a negligible impact on the future crop trees because of the generally high stocking levels following seed tree cuts. It is important to note that even large diameter seed trees are capable of strong growth following the regeneration harvest, so unacceptably low growth performance by the overwood is not a major concern. For locations where seed crop failure, arson, or other forest health problems (for example, prolonged drought) can threaten newly established pine seedlings, the longer retention of the overwood also acts as a buffer against complete loss (Lotti 1953).

Assuming mortality is limited, waiting to remove the seed trees can also significantly bolster the sawtimber yield of the stand, and may turn what would have otherwise been a precommercial thinning into a commercial one. Grano (1961) reported on some seed tree harvests on the CEF that did not have the overwood cut following the regeneration harvest. In these stands, approximately 13 seed trees at least 10 inches in diameter per acre were retained. After 21 years, the stand was thinned for the first time, and over 6,800 board feet (International 1/4 inch rule) per acre of sawtimber was harvested, primarily from the old seed trees. Using techniques and equipment consistent with that period of time, less than 14 percent of the regeneration on these sites was lost to logging damage, even though 31 to 42 square feet per acre of pine greater than 10 inches d.b.h. were felled (Grano 1961). Modern mechanized operations may produce more damage, but if fewer seed trees are reserved and done in conjunction with a planned thinning, these losses can be controlled, especially if using directional felling and the tops are removed prior to skidding.

CONCLUSIONS

This study highlights some of the promises and challenges to using seed tree methods to manage loblolly and shortleaf pine stands in the Upper West Gulf Coastal Plain. Though stand-level growth was limited due to mortality, individual seed tree growth rates were strong. In general, the smallest diameter seed trees grew the fastest (in terms of percent volume) and represented the lowest risk of mortality-based volume loss. Given that seed production is rarely limiting in mixed loblolly/shortleaf pine stands, the silviculturist needs to weigh the risk of seed tree loss with the potential for future growth. Fortunately, the good regeneration that typically follows seed tree harvests, coupled with the commercial potential of the overwood, allows for many different options to be evaluated at the landowner's discretion, rather than forcing a particular decision because of the economic pressures of high establishment and maintenance costs.

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SELF-REFERENCING SITE INDEX EQUATIONS FOR UNMANAGED LOBLOLLY AND SLASH PINE PLANTATIONS IN EAST TEXAS

Dean W. Coble and Young-Jin Lee[1]

Abstract—The Schnute growth function was used in this study to model site index for unmanaged or low-intensity managed loblolly pine (*Pinus taeda*, L.) and slash pine (*Pinus elliottii*, Engelm.) plantations in east Texas. The algebraic difference approach was used to derive an anamorphic base-age invariant site function that was fit as a fixed base-age anamorphic site function (base age = 25 years). The dataset was comprised of 1,135 and 502 serially correlated height-age observations of loblolly and slash pine, respectively, which were collected over a 20-year-period as a part of the East Texas Pine Plantation Research Project (ETPPRP). The new site functions represent an improvement over earlier site functions for east Texas, especially for slash pine, primarily because the new function accounted for serial correlation in the data. The new site index equations apply to unmanaged or low intensity managed loblolly and slash pine plantations in east Texas ranging in age from 5 to 40 years.

INTRODUCTION

Mathematical models or functions have been used extensively to describe site-age relationships. Dynamic site functions are a particular type of mathematical function that are defined by their own value at some reference point in time, which is called the initial condition (Cieszewski 2002). Thus, they are self-referencing (Northway 1985) with the initial conditions defined by data. They also possess the property of base-age invariance (Bailey and Clutter 1974). Base-age invariance means that the selection of a base age (index age) has no effect on the parameter estimates. Bailey and Clutter (1974) introduced a technique to derive dynamic site functions called the Algebraic Difference Approach (ADA). Base-age invariant site functions derived via ADA have the general form: $H_2 = f(H_1, A_1, A_2)$, where H_2 = height at A_2, H_1 = height at A_1, A_2 = Age at time 2, and A_1 = Age at time 1. Fixed base-age site functions have the general form: $H = f(S, A, A_0)$, where H = height at A, S = Site index, A = age, A_0 = index age for site index. Site index (and index age) must be known prior to model fitting for fixed base-age site functions; however, it need not be known *a priori* for base-age invariant site functions. Cieszewski and others (2000) present a detailed discussion of base-age invariant and fixed base-age site functions.

Sigmoid growth functions (e.g., Chapman-Richards; Chapman 1961, Richards 1959) have been used for decades to predict site index (Pienaar and Turnbull 1973, Newberry and Pienaar 1978, Clutter and others 1983, Lenhart and others 1986). Schnute (1981) generalized these sigmoid growth functions into one model. Coble and Lee (2006) used Schnute's model as the guide curve (Clutter and others 1983) to develop a family of anamorphic site curves for loblolly and slash pine plantations in east Texas. They ignored the serial correlation in the remeasured plot data used to develop the guide curve. The purpose of this study was to derive a base-age invariant version of Schnute's model and use Northway's fitting method to account for serial correlation in the hopes to improve site index estimates over those of Coble and Lee (2006).

METHODS

Schnute Growth Function

The integrated form of Schnute's second-order differential equation was used in this study:

$$Y(t) = \left\{ y_1^b + \left(y_2^b - y_1^b \right) \frac{1 - e^{-a(t-\tau_1)}}{1 - e^{-a(\tau_2 - \tau_1)}} \right\}^{1/b} \quad (1)$$

where,

Y(t) = size of organism at time t,
y_1, y_2 = size of organism at τ_1 and τ_2,
τ_1, τ_2 = ages at time 1 and 2 (e.g., old and young), and
a, b = constants to be estimated via regression ≠ 0.

The Algebraic Difference Approach (ADA) of Bailey and Clutter (1974) was applied to Equation 1 to derive a base-age invariant anamorphic site function. First, solve Equation 1 for the initial conditions, H_0 and t_0:

$$H_0 = \left\{ y_1^b + \left(y_2^b - y_1^b \right) \frac{1 - e^{-a(t_0-\tau_1)}}{1 - e^{-a(\tau_2 - \tau_1)}} \right\}^{1/b}$$

Then, solve for the site-specific parameter, y_2^b:

$$y_2^b = y_1^b + \left(H_0^b - y_1^b \right) \frac{1 - e^{-a(\tau_2-\tau_1)}}{1 - e^{-a(t_0 - \tau_1)}}$$

Substituting this expression in Equation 1 gives the base-age invariant anamorphic site function:

$$H = \left(y_1^b + \left(H_0^b - y_1^b \right) \frac{1 - e^{-a(t-\tau_1)}}{1 - e^{-a(t_0 - \tau_1)}} \right)^{1/b} \quad (2)$$

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where all variables are defined as before. Equation 2 represents a base-age invariant anamorphic site function described by the Schnute growth function. The formulation of equation 2 follows that of ADA functions if the following substitutions are made: $H_2 = H$, $H_1 = H_0$, $A_2 = t$, and $A_1 = t_0$.

Model Fitting Procedure

Northway (1985) presented a methodology for fitting self-referencing functions to serially correlated data. His procedure requires an estimate of H_0 at t_0 prior to the fitting process, which is a problem since H_0 at t_0 is rarely measured in the field. Northway (1985) referred to this estimate of H_0 and t_0 as site index (S) at the index age (t_{IA}). Equation 2 was reformulated as a fixed base-age site function to accommodate this change of variables:

$$H = \left(y_1^b + \left(S^b - y_1^b \right) \frac{1 - e^{-a(t - \tau_1)}}{1 - e^{-a(t_{IA} - \tau_1)}} \right)^{1/b} \quad (3)$$

where all variables defined as before. Each remeasured plot provided a growth series from which estimates of S were calculated during the iterative nonlinear fitting process. Each record in the dataset contained a single height-age pair, along with its entire growth series, which is every height-age pair for the specific plot measured over time. As explained below, this growth series was used to estimate S for each height-age pair.

To estimate S for each height-age pair, initial estimates of the regression coefficients (i.e., a and b) were first set in equation 3. These initial estimates corresponded to starting values in the iterative nonlinear fitting process, and they changed with successive iterations. Within each iteration, conditional site index estimates (CSI) were set in equation 3. Heights were predicted for the entire growth series for the values of CSI. The squared differences (observed – predicted) in height were then calculated. The values of CSI for the current iteration that minimized the squared differences were used as final S estimates to estimate new values of the regression coefficients for the next iteration. This process was repeated until the least squares error for the overall regression was minimized (i.e., lowest SSE). Thus, CSI is the estimate of site index that minimizes squared differences of serially correlated observations, given the current coefficient estimates. Thus, the procedure simultaneously estimates S for the growth series and CSI used in the function. The "throw away" final CSI values are, in fact, excellent estimates of the height at the index age (25 years in this study) for each growth series.

Data Analysis

This study used the same data as Coble and Lee (2006), where 124 permanent plots were located in loblolly pine plantations, and 56 plots were located in slash pine plantations throughout east TX. The data were compiled differently in this study to work with the Northway (1985) methodology. The ETPPRP study area covers 22 counties across east TX (Lenhart and others 1985). Generally, the counties are located within the rectangle from 30–35 north latitude and 93–96 west longitude. Each plot consists of two subplots: one for model development and one for model evaluation. A subplot is 100 by 100 feet in size, and a 60 foot buffer separates the subplots. All planted pine trees are permanently tagged and numbered. Only the model development plots were used in this study. The average height of the ten tallest site trees and the total age of the plantation were used to represent height and age in the functions. The ten tallest trees per plot (40 trees per acre) were considered site trees if they met the following criteria: 1) free of damage, 2) no forks, and 3) no presence of stem fusiform rust (Cronartium quercuum [Berk.] Miyabe ex Shirai f. sp. Fusiforme). Plots were remeasured every three years; some plots only provided two observations (six years), while some provided eight observations (24 years). A total of 1,135 remeasured height-age observations for loblolly pine and 502 remeasured height-age observations for slash pine (table 1) were used to fit equation 3. PROC NLIN in SAS version 9.1 was used to run the analyses.

RESULTS AND DISCUSSION

Equation 3 was fit to the loblolly and slash pine data to produce the coefficients in table 2. All coefficients were significantly different from zero, and the residual plots did not reveal any unusual heteroscedasticity problems (plots not shown). Note that $y_1 = \tau_1 = 1$, which corresponds to a one-year-old seedling that is one foot tall; these fixed values were based on measurements of the youngest trees in the datasets. Also, index age = τ_{IA} = 25 years. The regression coefficients a and b were estimated by SAS. The coefficient values from table 2 were used in equation 3 to produce site

Table 1—Descriptive statistics for the ETPPRP loblolly and slash pine development plots, where age = total age of plantation and height = average height of the ten tallest site trees on a plot

Species	Variable	N	Mean	Standard deviation	Minimum	Maximum
Loblolly	Age *(years)*	1,135	14	7	1	37
	Height *(feet)*	1,135	44	21	1	94
Slash	Age *(years)*	502	14	7	1	33
	Height *(feet)*	502	44	21	2	91

Table 2—Parameter estimates and fit statistics of loblolly and slash pine site functions (Equation 3)

Species	Parameter	Parameter estimate	Standard error	Lower 95% confidence interval	Upper 95% confidence interval	Root MSE (*feet*)
Loblolly	y_1	1	na	na	na	2.7
	a	0.0690	0.00285	0.0634	0.0746	
	b	0.7291	0.0198	0.6904	0.7679	
	$_1$	1	na	na	na	
	$_{IA}$	25	na	na	na	
Slash	y_1	1	na	na	na	2.5
	a	0.0401	0.00423	0.0318	0.0484	
	b	0.8769	0.0314	0.8152	0.9386	
	$_1$	1	na	na	na	
	$_{IA}$	25	na	na	na	

curves for loblolly pine (fig. 1) and slash pine (fig. 2). These curves range in site index from 40 to 90 feet (index age = 25 years), and they apply to plantations that range from 5 to 40 years of age.

The precision of the parameter estimates (standard errors for a and b) and overall regression (RMSE) were higher for the self-referencing function than the guide curve function of Coble and Lee (2006) for both loblolly and slash pine (table 3). In fact, the guide curve function RMSE was double the value for RMSE of the self-referencing function.

For loblolly pine, the shapes of the self-referencing site curves were similar to those based on the guide curve of Coble and Lee (2006) (fig. 3). Shapes were compared for site indexes of 40, 60, and 80 feet by taking the difference between the site index values of the self-referencing and Coble and Lee (2006). The largest differences were less than three feet, and these occurred above 30 years of age. For slash pine, the shapes were dramatically different between the self-referencing curves and those of Coble and Lee (2006) (fig. 4). Differences ranged from approximately 3 to 10 feet for ages greater than 30 years. Differences were not as great for younger ages. Thus, the self-referencing site functions seem to better capture the curve shape better for older ages than the functions of Coble and Lee (2006). We attribute this improvement to the self-referencing functions capturing the effect of serial correlation in the data. Both this study and Coble and Lee (2006) used the Schnute (1981) model and the same dataset; however, Coble and Lee (2006) ignored the serial correlation of the data.

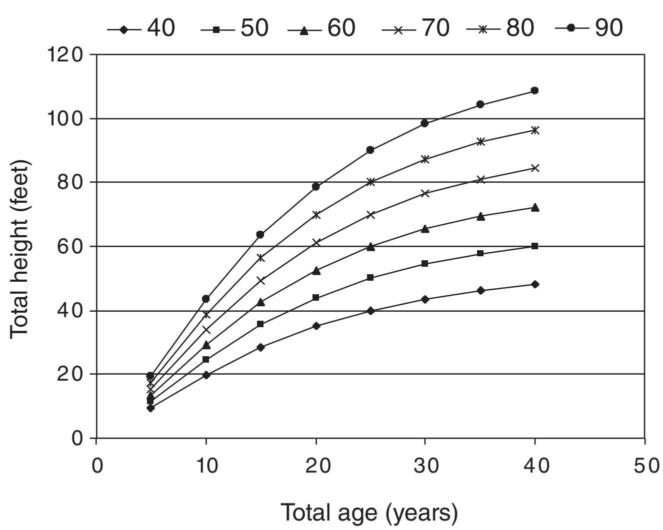

Figure 1—Site index curves (index age = 25 years) for unmanaged loblolly pine plantations in east Texas.

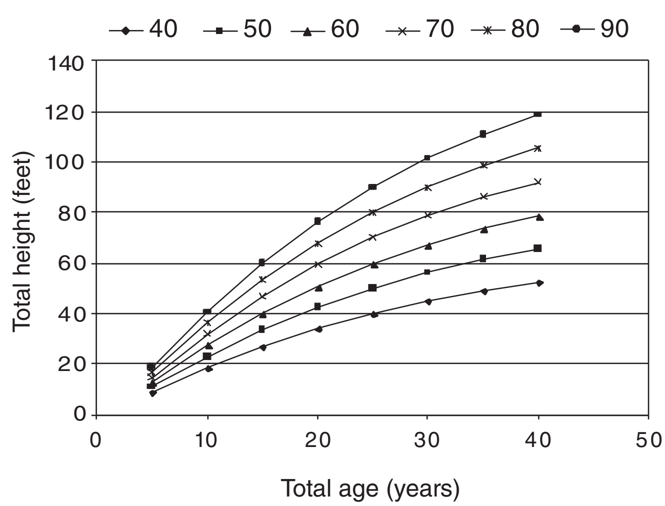

Figure 2—Site index curves (index age = 25 years) for unmanaged slash pine plantations in east Texas.

Table 3—Comparison of overall precision and the precision of the parameter estimates for the self-referencing site functions of this study and the guide curve functions of Coble and Lee (2006)

Species	Function	RMSE	SE(a)	SE(b)
Loblolly	Guide Curve	7.3	0.0034	0.0401
	Self-referencing	2.7	0.0029	0.0198
Slash	Guide Curve	6.7	0.0055	0.0648
	Self-referencing	2.5	0.0042	0.0314

Note: RMSE = root mean square error in feet and SE = standard error in feet.

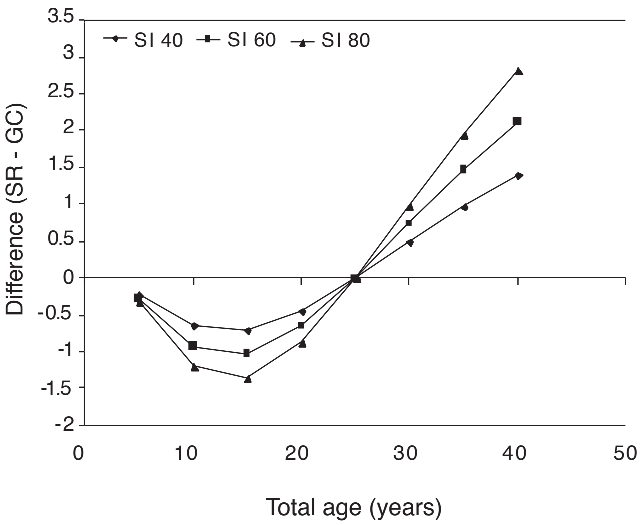

Figure 3—Comparison between the self-referencing curves of this study (SR) and curves of Coble and Lee (2006) (GC) for loblolly pine. Note that SI = site index in feet (base age = 25 years).

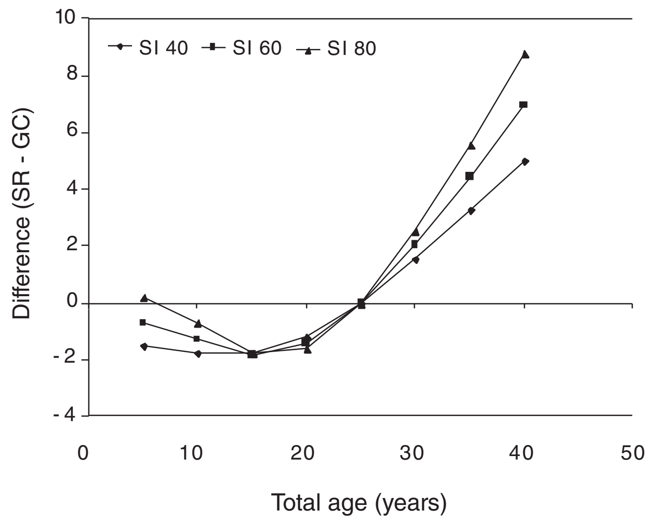

Figure 4—Comparison between the self-referencing curves of this study (SR) and curves of Coble and Lee (2006) (GC) for slash pine. Note that SI = site index in feet (base age = 25 years).

CONCLUSIONS AND RECOMMENDATIONS

The self-referencing version of the Schnute growth function represents an improvement over Coble and Lee (2006). For both loblolly and slash pine, overall model precision is doubled and standard errors of regression coefficients are reduced for the new function in this study compared to Coble and Lee (2006). Differences in site curve shape between the two functions were most dramatic for slash pine than loblolly pine. The differences were most pronounced for older plantations (age > 30 years). These improvements were attributed to accounting for serial correlation in the data used to build the site function, which Coble and Lee (2006) ignored. The new curves in this study are applicable to unmanaged, or low-intensity managed, loblolly and slash pine plantations in east TX.

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CONSEQUENCES OF A FIXED-TOP DOB ASSUMPTION ON THE ESTIMATION OF PINE CHIP-N-SAW AND SAWTIMBER TONS

G. Kenneth Xydias[1]

Abstract—Many pine plantation growth and yield simulators allow the user to define products based on the size classes and top diameters corresponding to local market specs. Top d.o.b. is typically set at a constant corresponding to the local product specification. Examination of individual tree data collected in cruises of loblolly pine stands across the South show that the top d.o.b. for pine products is not a constant, but varies directly with d.b.h. Median overstatement of individual tree PST volume due to use of a fixed 6 inch d.o.b. top instead of the top d.o.b. implied from merchantable height is about 10 to 15 percent, but can range from zero to almost 400 percent. Volume overstatements at the stand level are more muted. PST is in the range of 0-149 percent and with a median value of about 16 percent. CNS and PPW have smaller ranges (0-60 percent) and median overstatements of about 8-10 percent. These overstatements are inversely related to the ratio of merchantable height divided by total height. PST overstatement was less than ten percent only when height ratio averaged 0.75 or more. Overstatements of 100 percent or more occurred when the product height ratios drops below about 0.35. Overstatements are not associated with stand attributes or geographical location in any meaningful way.

INTRODUCTION

Pine products generally recognized in the South include pulpwood (PPW), chip-n-saw (CNS), and sawtimber (PST). Other products including canter wood, poles, ply-logs, etc. may be recognized as well depending upon geographical location or market region. However a discussion of them is not germane to this paper.

Each of these products is defined in the market by d.b.h., a minimum merchantable height and a minimum top diameter. In addition certain quality characteristics must be present before a tree can qualify for CNS or PST. These include straightness, and the absence of large limbs, surface defect, ring or whorled knots, and forks within the portion of the stem associated with these two products.

Merchantable height may be limited by the top d.o.b. associated with the product specification or by the quality factors just mentioned. One definition of merchantable height is that point where the sum of branch diameters within any one-foot section exceeds some percentage of stem diameter at that point and where there is less than eight feet of clear stem large enough to qualify above that point. Values range from thirty percent (pers. comm., Tom Carignan, Carignan Forestry Consultants, www.Carignan.net) to one hundred percent (Clark and McAlister 1998).

Growth and yield models are widely used to provide estimates of product volume. Examples of these models include Baldwin and Feducia (1987), Burgan and others (1994), Burkhart (2003), Chang (2005), and many others. Citations are meant to be examples, and are by no means exhaustive.

The merchandising routine of these models calculates product volume to the top d.o.b. specified by the user for each product. That value is generally set at the value called for by each product. That same assumption is occasionally made in working up a cruise.

This analysis evaluates whether it is reasonable to assume that products terminate at the top d.o.b. used to define the each product, and if not, the magnitude of bias that may be expected to occur when that assumption is not met.

METHODS

Data for this analysis came from stand level cruises done by experienced cruisers. More than 3,000 stands across the South were inventoried using commonly accepted practices. Prism plots were always used, and prism factors were either 10 or 20, depending upon stand basal area. D.b.h. was estimated to the nearest inch, and merchantable height was estimated to the nearest half-log. Total height was measured across a range of diameters in some stands and for dominant and codominant trees in other stands. Merchantable height was not estimated for some stands; instead cruisers estimated the diameter at the merchantable top. Site quality was determined for each stand in an independent process.

Product calls were based on individual tree quality and local product specs. The CNS diameter range was 8 to 11 inches and the PST diameter range was 10 inches and larger. Consequently trees in the 10- and 11-inch classes could represent either product. In general, the 10-inch minimum sawtimber d.b.h. occurred in areas west of the Mississippi River where CNS was generally not recognized.

Analysis was done both at the tree level and at the stand level. The tree level analysis was restricted to a 9,600 tree subset of loblolly pine with data for both total and merchantable height. Trees in this subset were from both planted and natural stands, and were in geographical regions where the product specification for PST was either a 6-inch or an 8-inch d.o.b. top. The top d.o.b. of each tree in this subset was calculated by a taper equation developed for planted loblolly stands that had been thinned (Baldwin and Feduccia 1987). Almost three percent of the trees in this subset had a calculated top d.o.b. that was in the 4-inch class or smaller. These trees were discarded from the

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analysis. About 16 percent of the trees had a calculated top d.o.b. in the 5-inch class, and these trees were retained in the analysis. A factorial ANOVA was done to evaluate the main effects of d.b.h., origin, the spec top d.o.b. along with their interactions on the top d.o.b. estimated by the taper equation. All statistical analysis was done using procedures in STATISTIX 8.0 (Anonymous).

The stand level analysis was restricted to loblolly pine plantations occurring in geographical regions where the product specification for top d.o.b. was 6.0 inches for both CNS and PST. About 1,200 stands cruised with ten or more plots from the 3,000 stand dataset were used for this analysis. Merchantable tons by product were calculated for each stand under two different assumptions of top d.o.b. One was to assume that the top d.o.b. went to the 6.0 inch top specified for each product. The other way was to use the top d.o.b. calculated by the same taper equation used in the tree level analysis. If the calculated top d.o.b. was less than the product specification, then the product specification was used. These two workup methodologies are referred to as fixed top and variable top workups respectively.

Since total height was collected on only a small number of trees, it was estimated for the remaining trees with the lower coastal plain diameter-total height equation reported in Harrison and Borders (1996). That equation in turn requires information about dominant height, which was not measured as part of the cruise protocol. Consequently it was estimated for each plot by different methodologies. These were in decreasing order of priority, a) average total height of measured trees at each plot whose diameters were at least as large as plot qmd, b) as above, but for trees whose total height was estimated by a diameter-total height equation developed for stands with such data, c) the average height calculated by either of the two previous methodologies, d) the average total height of measured trees in stands where the diameter-total height equation was not significant, or e) the dominant height implied by stand age and site quality.

RESULTS AND DISCUSSION

Tree level

Results from the factorial ANOVA evaluating the main effects of d.b.h., stand origin, and spec top d.o.b. on the calculated merchantable top d.o.b. are shown in table 1 for PST trees in the 12-17 inch d.b.h. classes. The lower d.b.h. value was chosen since that was the minimum d.b.h. for PST in the region where the product specifications called for an 8-inch d.o.b. top. The upper limit was set because there were insufficient trees in the larger d.b.h. classes to have a reasonable number of observations across all cells.

The ANOVA suggests that the only main effects that were significant were d.b.h. and stand origin. The effect of regions where the cruise specification for PST called for either a 6-inch or an 8-inch d.o.b. top was not significant. That suggests that merchantable height for 12-inch and larger PST is limited more by tree quality factors than the top d.o.b. specification. None of the interactions were significant.

Stand origin was significant at the five percent level, but differences in the mean top d.o.b. between planted and natural stands were only about 0.2 inch. This result would likely have been different if the top d.o.b. had been calculated using equations developed from each of these two stand types.

The effect of d.b.h. on top d.o.b. was highly significant ($P<0.01$). The average top d.o.b. increased about 0.4 inch with each one-inch increase in d.b.h. class.

Similar results occurred when the ANOVA was done with a wider range of d.b.h. classes, but restricted to the region where the top d.o.b. specification for both CNS and PST was 6.0 inches. The summary table for this analysis is shown in table 2.

Both of these analyses suggest that the top d.o.b. is driven by d.b.h. rather than the product specification for top d.o.b. That would imply merchantable height is limited more by tree quality factors than the product specification. These analyses also show that the effect of origin on top d.o.b. is small relative to the influence of d.b.h. Consequently it would seem that little error would be introduced by combining trees from both planted and natural stands when evaluating the effect of d.b.h. on top d.o.b.

The distribution of estimated top d.o.b. values by d.b.h. class is shown as a box and whisker graph in figure 1. The lower and upper horizontal lines of each box represent the 25th and 75th percentiles respectively. Each whisker represents one quarter of the percentile distribution. It can be seen that median values are close to the values defined by the product specification only for trees in the 8- and 9-inch-diameter classes. As d.b.h. increases beyond that value, so does the median value for top d.o.b. About 75 percent of the trees in the 11-inch class had a top d.o.b. greater than the spec top. This increased to 100 percent at the 15-inch d.b.h. class.

It should be clear from figure 1, that the top d.o.b. observed across a wide range of diameter classes is larger than the top d.o.b. called for by the product specification. It is clearly not a constant, but a variable whose value changes with d.b.h. Similar results have been reported elsewhere. Westfall (2006) showed that use of a taper equation to predict merchantable height to a fixed top d.o.b. overstated merchantable height, and the amount of overstatement increased with d.b.h.

The issue is how much additional chip-n-saw and sawtimber volume will be calculated for each d.b.h. class when that volume is calculated to a fixed top d.o.b. relative to the median values shown in figure 1. An Excel spreadsheet was developed to calculate the hypothetical diameter distribution and total height by d.b.h. class for a specified set of stand attributes. Equations used were those reported in Harrison and Borders (1996) for the lower coastal plain. That data was used to calculate merchantable tons to both a fixed 6-inch d.o.b. top and to the median top d.o.b. values of figure 1. For this example, the stand was assumed to be age 25, site 75, and stocked with 150 trees per acre.

Results are shown in figure 2. The overstatement, shown on the Y-axis, is the additional tons to a 6-inch d.o.b. top expressed

Table 1—ANOVA for DBH, origin, and spectop for pine sawtimer in the 12-17 inch diameter range

Source	DF	SS	MS	F	P	
DBH	5	745.45	149.09	76.2	0.001	***
Origin	1	12.65	12.64	6.5	0.011	*
SpecTop	1	0.94	1.94	1.5	0.220	NS
Dbh x Origin	5	1.00	0.38	0.2	0.966	NS
Dbh x SpecTop	5	1.88	2.60	1.3	0.249	NS
Origin x SpecTop	1	12.98	0.70	0.4	0.551	NS
Dbh x Origin x SpecTop	5	0.70	1.55	0.8	0.554	NS
Error	-	7.77	1.96	-	-	
Total	-	7705.12	-	-	-	

*** Differences due to dbh are 0.4+ inches for each dbh class.
* Differences due to origin are about 0.2 inch.

as a percentage of tons based on the median values of figure 1. The relationship between d.b.h. and volume overstatement depends upon whether all trees are considered, or only those whose calculated top d.o.b. was in the 6-inch class or larger. For this latter case, there is a more or less linear relationship between d.b.h. and volume overstatement. For the former case, volume overstatement increases sharply with d.b.h. to about the 12-inch class and more slowly thereafter.

Figure 2 implies that the average volume overstatement varies with d.b.h., is about the 2-9 percent range for CNS and 10-15 percent for PST through the 17-inch class. It is in the 15-20 percent range for trees whose d.b.h. is 18+ inches.

The trend shown in figure 2 is not strongly influenced by age or site quality. The percentage overstatement declines slightly as these attributes increase. The point to note is that specification of a single fixed top d.o.b. by product will likely result in volume overstatements that may not be trivial. More accurate estimates can only be obtained by allowing the top d.o.b. to vary with d.b.h.

An alternative way of expressing the top d.o.b. is to define it as a proportion of d.b.h. That definition will subsequently be referred to as top ratio. The relationship between top ratio and d.b.h. is shown is shown as a box and whisker graph in figure 3. As can be seen, top ratio declines rapidly with increases in d.b.h., but trend toward stability when d.b.h. is in the range of 12-13 inches and greater. At that point, median values are in the range of 0.55-0.60.

Top d.o.b. calculated as the product of median values of figure 3 and d.b.h. will result in the same median values shown in figure 1. The advantage of specifying top d.o.b. as a proportion of d.b.h. from a growth and yield standpoint is twofold. First, the calculated volumes will be closer to actual values on average, and second, the top d.o.b. for sawtimber size trees can be characterized with a single input variable.

Examination of figure 3 shows that there is considerable variability about the median values. For any one d.b.h. class, the top d.o.b. could be as low as 40 percent or as high as 90 percent of d.b.h. This variability is due to variation in the ratio of merchantable height divided by total height. That ratio will be referred to as height ratio in the remainder of this discussion. Another term, often found in the literature, is relative height.

Table 2—ANOVA for DBH and origin of pine cns and sawtimber in the 8-20 inch diameter range

Source	DF	SS	MS	F	P	
DBH	12	8131.60	677.60	493.8	0.017	*
Origin	1	10.60	10.60	7.7	0.006	***
Dbh x Origin	12	20.90	1.74	1.3	0.966	NS
Error	10109	13871.00	1.37	1.3	0.230	NS
Total	10134					

* Differences due to dbh are 0.4+ inches for each dbh class.
*** Differences due to origin are about 0.2 inch.

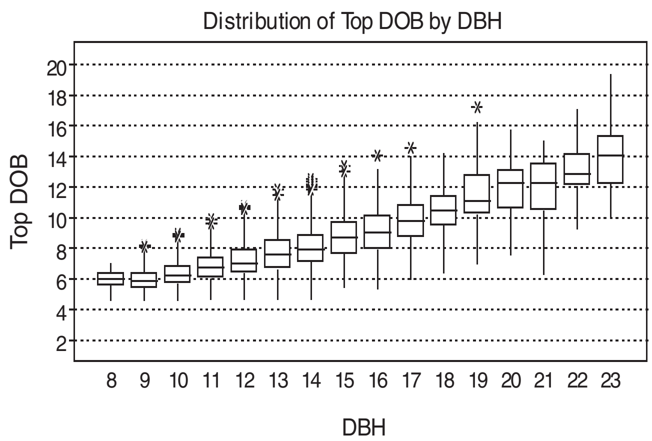

Figure 1—Variability in estimated top d.o.b. by d.b.h. class.

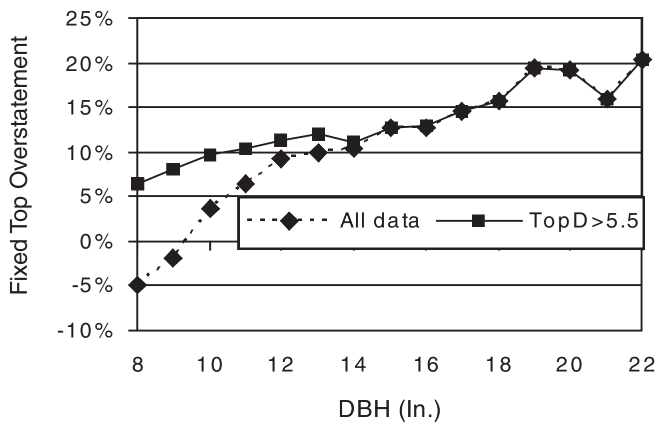

Figure 2—Volume overstatement due to assumption of a fixed 6-inch d.o.b. top.

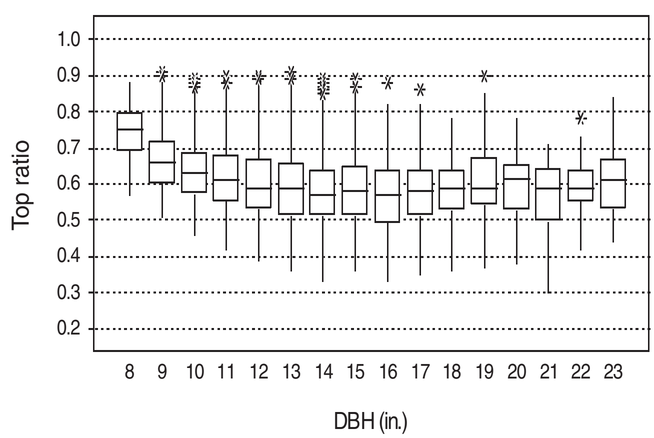

Figure 3—Top d.o.b. as a proportion of d.b.h.

There was nearly perfect correlation between diameter ratio and height ratio. That near-perfect relationship is an artifact of the analysis and would not have been near as good had actual top d.o.b. been available. It suggests however that height ratio is an important determinant of top d.o.b., and of the volume overstatement that could occur when a fixed top d.o.b. is assumed.

Volume overstatement was calculated using the individual tree data subset. The relationship between volume overstatement and both height ratio and merchantable height is shown in figure 4.

Volume overstatement at the tree level ranges from less than zero to almost 400 percent. Negative overstatements occur because the calculated top d.o.b. was less than 6.0 inches for some trees. Height ratios are in the range of 0.2 to a little over 0.8, and merchantable height ranges from 16 to almost 90 feet. Large overstatements are associated with small height ratios or trees whose merchantable height is short relative to their total height. Overstatements of 100 percent or more seem to be restricted to trees with 32 feet or less of merchantable height. However these trees may also have a negligible overstatement except for those trees with only 16 feet of merchantable height. Overstatements are small where height ratios are large or where trees have five to six logs of merchantable height.

Stand level

The tree level analysis discussed in the previous section has shown that the volume overstatement due to the assumption of a fixed top d.o.b. varies directly with d.b.h. Furthermore, since top d.o.b. is inversely related to merchantable height, volume overstatement varies inversely with height ratio. This section will show that the volume overstatement at the stand level for the various pine products is also inversely related to the average height ratio for each product.

The stand level analysis was done using about a 1,200 stand subset of the 3,000 cruised stand database. Stands in this subset were restricted to loblolly pine plantations cruised with a minimum of ten plots and occurring in areas where the product specification for both CNS and PST included a 6-inch d.o.b. top. Merchantable tons were worked up for each stand using both a 6-inch d.o.b. top, and a top d.o.b. implied by merchantable height. These two workup methodologies will be referred to a fixed top workup and a variable top workup respectively.

Data items calculated from this subset include volume overstatement as defined previously, height ratio by product, and a fixed top reduction factor. Product height ratio is the average height ratio calculated from all trees tallied as that product for each cruised stand. The fixed top reduction factor is the inverse of volume overstatement. It is simply a factor which when multiplied by a growth and yield estimate of product volume (fixed 6-inch d.o.b. top workup) will result in the volume calculated by a variable top workup.

Results are shown in figure 5 for PST on the left and for CNS on the right. Results for PPW are similar and won't be shown. It is clear from these two graphs that the relationship

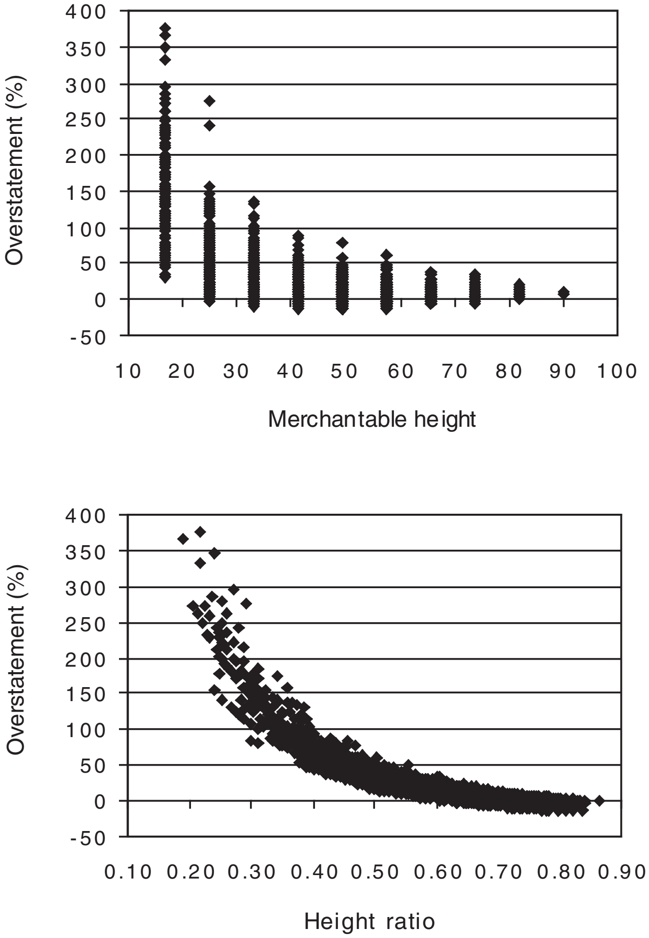

Figure 4—Overstatement as influenced by both height ratio and merchantable height.

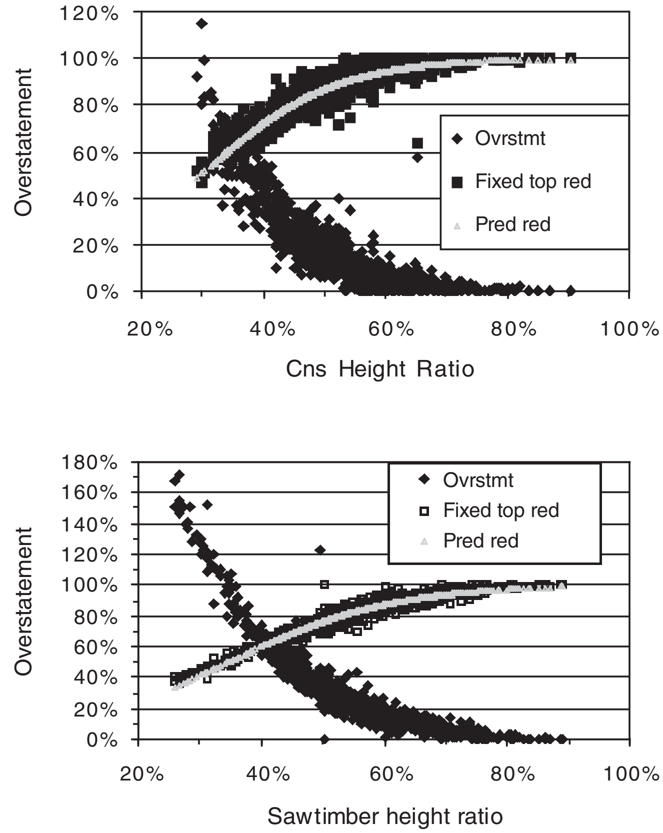

Figure 5—Overstatement, fixed top reduction, and predicted reductions related to average height ratio at the stand level for PST (left graph) and for CNS (right graph).

between average height ratio for a particular product at the stand level and volume overstatement of that product is similar to the relationship observed at the tree level (fig. 4).

Overstatements for PST range up to almost 170 percent, while overstatements for CNS range up to about 120 percent. The larger overstatements we re associated with stands containing less than five tons/acre of product. But a graph of all stands with less than five tons per acre of product does not appear to be different from the graphs shown in figure 5.

The growth and yield reduction factor is in the range of 0.4 to 1.0. As with volume overstatement, the reduction factor is inversely related to product height ratio.

Stepwise logistic regression was used to determine what stand variables were related to calculated values of growth and yield reduction factor for each product. The only variable having significance at the five percent level was height ratio. Predicted values show that product height ratios must be at least 60 percent or more in order for the volume reduction factor to be at least 0.9 when volume workups are to a fixed 6-inch d.o.b. top. Another way of stating that is that if product height ratios drop below 60 percent, then volume workups based on actual top d.o.b. will be around 90 percent or less of fixed top workups.

The distribution of actual and cumulate overstatement by product is shown in figure 6. These distributions are peaked and highly skewed to the right. Modal overstatements for PPW and CNS are about five percent. The modal overstatement for PST is about 16 percent. The median overstatement was about 8, 10 and 16 percent for PPW, CNS, and PST respectively. Overstatements at the 95th percentile were 30, 55, and 80 percent for these products respectively. This graph shows that estimates of higher-value products based on a fixed top workup assumption tend to be liberal, and that the amount of product overstatement increases with product value.

It should be noted that the results shown here are not based on field measurements of top d.o.b. and total height. Recall that top d.o.b. was estimated from a taper equation. In addition, total height was estimated from a diameter-total height equation where dominant height was one of the regressor variables. Dominant height in turn was seldom measured, but was estimated from different sources. While it could be argued that the results are simply an artifact of the analytical methodology, additional lines of evidence suggest that is unlikely.

Drs. Honorio Carino and David Smith of Auburn University have graciously provided a dataset of 160 trees from three loads of long wood delivered to a local wood yard. Variables measured for each tree in that dataset included d.b.h., merchantable length and top d.o.b. The stand level cruise dataset provided

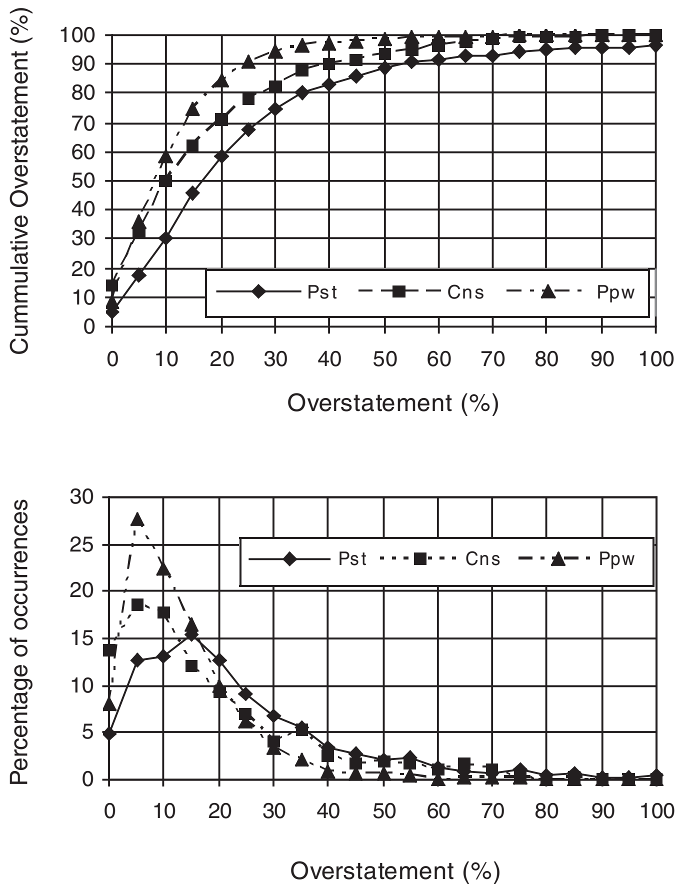

Figure 6—Distribution of overstatement: frequency on the left and cumulative on the right.

a second line of evidence. Top d.o.b. was estimated by the cruisers for many of the stands cruised. Finally, a property-level cruise in northcentral AL, where both merchantable and total height was estimated for each tree provided a third line of evidence. For this dataset, top d.o.b. was estimated with the same taper equation used for the stand-level cruise dataset.

Simple linear regressions predicting top d.o.b. from d.b.h. and merchantable height were done separately for each of these additional datasets. R-squared values were in the range of 0.80 to 0.85 except when the dependent variable was cruiser estimate of top d.o.b. For that case, it was around 0.50. A diameter range of 8-18 inches was specified, and merchantable height values, typical of those for each d.b.h. class were assumed. Top d.o.b. predicted by the equations derived from each dataset was plotted against D2H values. Results are shown in figure 7.

The direct measurements of top d.o.b. from the wood yard data resulted in diameters that were more than an inch larger than those from those predicted from the cruise data set. Top d.o.b. based on cruiser calls were slightly larger than those predicted from the cruise data set. Values from the northcentral AL data set were somewhat smaller. Timber stands in this latter dataset were all unthinned loblolly pine plantations, so excessive limbiness is less likely to limit merchant table height. Consequently such trees would likely have had a greater merchantable length and a correspondingly smaller top d.o.b. than the average tree in the cruise data set.

The point to note is that these additional data sets fail to provide evidence that the results are an artifact of the analytical methodology. If anything, they show that the results presented could be conservative.

Additional research involving the direct measurement of the top d.o.b. associated with merchantable height would server to either confirm or refute these results. Merchantable height is a somewhat subjective concept except for obvious factors such as forks or crooks. Input from experienced timber buyers would aid in the design of a study protocol.

Attempts to relate PST height ratio to stand attributes such as basal area, trees per acre, age, etc. or to geographic locality were largely unsuccessful. The best R-squared values using stepwise regression relating stand attributes to height ratio were only in the range of 0.15 to 0.20.

It may seem reasonable to believe that geographical areas where natural agents such glaze storms or fusiform rust are common would have lower height ratios than geographic areas where these risks are infrequent. When stands were grouped into classes representing these hazards, the F ratio for a one-way ANOVA was not significant at the 0.05 level.

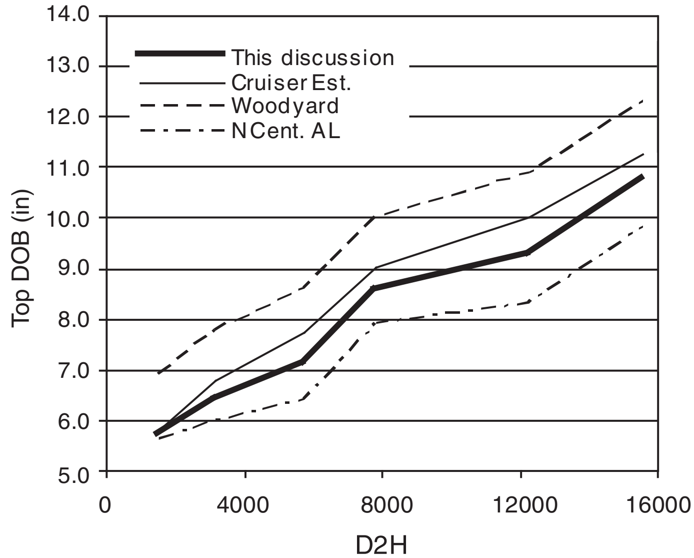

Figure 7—Comparison of top d.o.b. from this study with other data sources and methodologies.

There were significant differences among states or groups of states. Stands in eastern NC had significantly greater overstatements and significantly lower sawtimber height ratios than in other areas. For that region, PST overstatement averaged 30 percent and height ratio averaged 53 percent. But the differences in the mean values were not large, and there was considerable variability about them. When these stands were removed from the dataset, there were no significant differences in either PST overstatement or height ratio.

These results imply that abnormal PST height ratios can occur in any stand, but their occurrence cannot be predicted in advance of stand examination. Their influence on cruise estimates of product volume can be accounted for only by a data collection protocol and workup methodology that accounts for both total and merchantable height for those trees whose top d.o.b. is larger than the product specification.

It will be more difficult to incorporate merchantable height into growth and yield models. Little is known about how it varies with stand attributes or over time. Perhaps the best that can be done is to simply be cognizant that estimates may overstate product volumes by an amount that is not trivial.

Finally, financial analysis supporting low density management using growth and yield estimates of product values may overstate higher value product volume and value to the extent that the conclusions are questionable.

CONCLUSIONS

This analysis has shown that the merchantable top diameter for CNS and PST products is not the constant value associated with the product specifications. Instead it is a variable that is directly related to d.b.h. The assumption that it is a constant will commonly overstate product volume. In this study, volume workups to a fixed 6-inch d.o.b. top overstated CNS and PST volume by ten and sixteen percent respectively relative to variable top workups where top d.o.b. was implied from merchantable height. For PST in the 12-inch and larger d.b.h. classes, the estimated top d.o.b. averaged 55-60 percent of d.b.h. Modification of growth and yield systems to permit specification of top d.o.b. as a percentage of d.b.h. will reduce the overstatement for the average stand relative to what would occur when a fixed top d.o.b. is assumed across all d.b.h. classes. Product overstatement is also inversely related to height ratio or merchantable height divided by total height. Overstatement is small when height ratio is about 0.75 to 0.80 or greater. It can exceed 100 percent when height ratio for PST drops below 0.30 to 0.35. Differences in height ratio result in differences in top d.o.b.; trees with small height ratios have a large top d.o.b. Top d.o.b. can be in the range of 40 to 80 percent of d.b.h., depending upon height ratio. Top d.o.b. was not measured but estimated using equations developed for use with growth and yield models. While it could be argued that the results are an artifact of the analytical methodology, comparison with other datasets including direct measurements of logs in a wood yard suggest that they are realistic. Overstatements are at best weakly related to stand attributes or geographical locality. They can only be minimized from an inventory standpoint when estimates for both merchantable and total height are available for trees whose top d.o.b. is greater than the product specification.

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COMPARING DIAMETER GROWTH OF STANDS PRIOR TO CANOPY CLOSURE TO DIAMETER GROWTH OF STANDS AFTER CANOPY CLOSURE

Thomas J. Dean, D. Andrew Scott, Ray A. Newbold[1]

Abstract—Three models are compared for their ability to account for differences in diameter growth associated with different stages of stand development. Data for the comparisons were collected in young loblolly pine plantations treated variously at time of planting for the first 10 years since establishment. Neither the growth-growing stock model nor the accelerated development model accounted for differences in average diameter growth resulting from fertilization or herbaceous weed control. A morphological model based on coordinated development between crown size and stem size, however, appeared to successfully account for treatment differences in diameter increment.

INTRODUCTION

Diameter growth declines with advanced stages of development, making analyses of treatments causing wide disparities of growth difficult to interpret after a number of growing seasons. This situation is analogous to comparing mortality among stands grown on different site qualities: stands on better sites seem to have poorer survival than stands on poorer sites due to earlier self-thinning. Fertilization at time of planting and early release are known to hasten canopy closure relative to untreated counterparts (Will and others 2006). Since diameter growth slows after canopy closure, diameter growth of the treated stands can be slower than the untreated stands. Without some sort of normalization, growth comparisons among stands in different stages of development become tenuous if not meaningless.

Three models exist that could provide some basis for normalizing growth comparisons among stands in different stages of development. The objective of this study is to investigate the potential of these models to account for differences in rate of development on growth comparisons with data collected from young loblolly pine plantations subjected to early fertilization and weed control.

THE MODELS

Growth—Growing Stock Relations

One of the first hypothesized relations between stand growth and growing stock introduced into the English forestry literature was proposed by Langsaeter (1941). While the true nature of the curve relating total growth to growing stock is controversial (e.g., Zeide 2001), average tree growth is thought to be unrelated to stand density before the canopy closes: after canopy closure, it declines steadily. Long (1985) used relative density as a surrogate for growing stock allowing him to map stages of development on the hypothetical curve relating growth with growing stock (fig. 1). According to this model, differences in relative density will account for differences in diameter growth across stages of development.

Accelerated Development

Miller (1981) stated that in the absence of a permanent change in site nutrition, a stand's response to fertilizer could be treated as a simple reduction in rotation length. This has become known as the accelerated development hypothesis (Jokela and others 1989). According to this hypothesis, after a brief increase, tree growth will return to the curve characteristic of the site and advanced developmental stage (fig. 2). Miller (1981) proposed that tree size equated to developmental stage; consequently, diameter growth of treated and untreated trees should converge at some common tree dimension.

Tree Morphology

Crown dimensions and tree size have long been known to be correlated (Larson 1963). The interrelationship between leaf area, height to the median of leaf area, and stem diameter often agrees with what would be expected if the stem behaved as a beam uniformly bending from drag of wind moving through the crown (Dean and others 2002) (fig. 3a). A corollary of this relationship is that diameter increment of the average-sized tree can be predicted from the combined changes in the quantity of leaf area and height to its median (fig. 3b). According to this model, crown size and position will account for differences in diameter growth across stages of development.

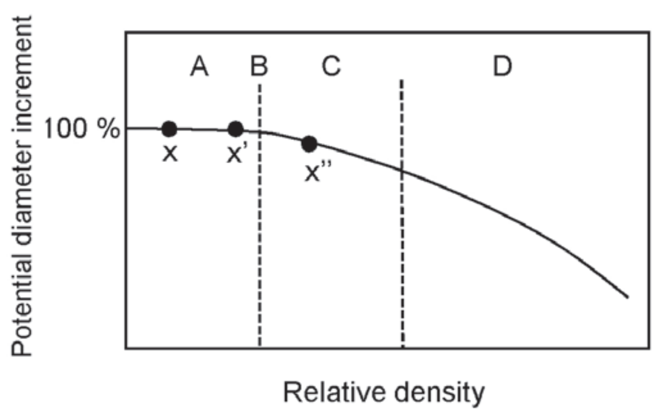

Figure 1—Growth-growing stock model for potential diameter growth as a functions of relative density and stage of stand development (A=open-grown; B=canopy closure; C=full-site; occupancy; D=self-thinning). x is a hypothetical stand at time t=0. x' and x" are stand x at t=1 if the stand were untreated or treated, respectively.

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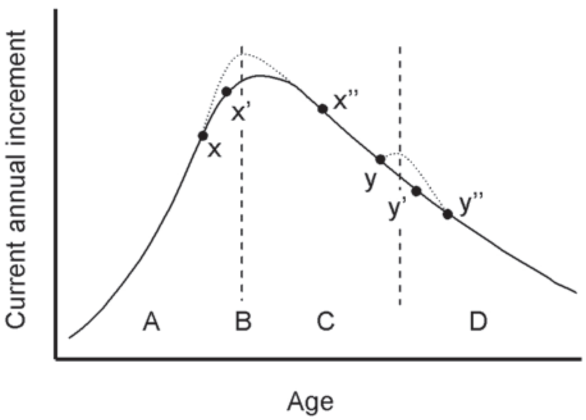

Figure 2—Miller's accelerated development hypothesis for the chronology of current annual increment (CAI) in relation to stage of development. Stages as in figure 1. Points illustrate effect of treatment on CAI (c.f., fig. 1).

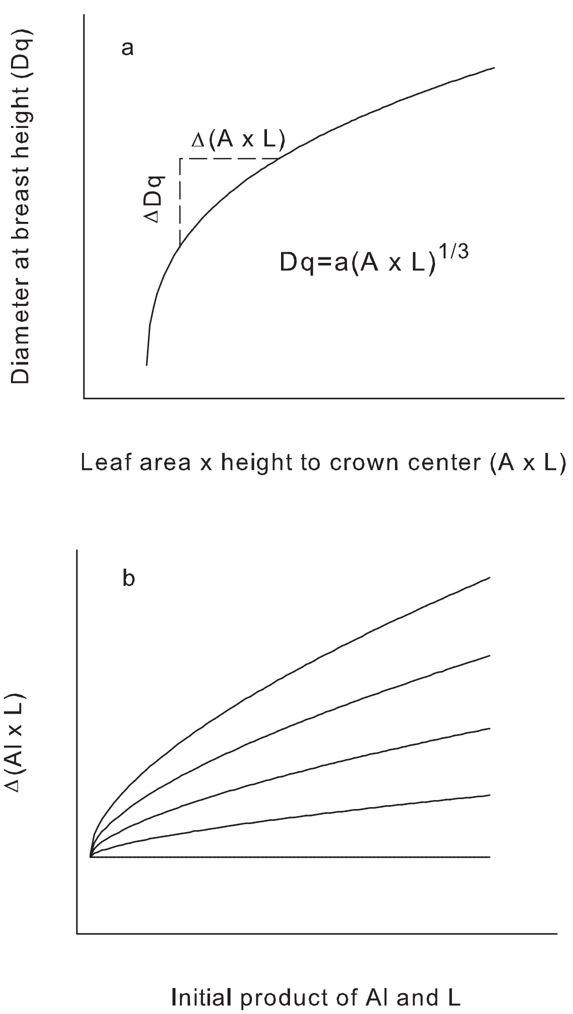

Figure 3—Tree morphology model. Relation between quadratic mean diameter (Dq) and mean product of leaf area (A) and distance to crown center (L) (a) and isolines of constant increment in Dq as a function of the mean change in (ΔAxL) and initial (AxL).

METHODS

Data from two experimental loblolly plantations were used for this study. The plantations are part of the Cooperative Research in Sustainable Silviculture and Soil Productivity, a partnership between forest industry, universities, and state and Federal agencies. The plantations selected for this analysis were established near Fred, TX and Bryceland, LA. The objectives and goals of the cooperative and details of these plantations are described in Carter and others (2006). These two plantations were selected because trees responded well to early cultural treatments of fertilization and herbaceous weed control (Dean 2001) and closed canopy sooner than the untreated trees.

Each site was blocked according to drainage or topography. Twenty-four, 0.074-ha plots were distributed uniformly between three blocks at Fred and four blocks at Bryceland and assigned factorial treatments at random. A standard pair of harvesting disturbances comprised one factor at each location (hand-felled, boles only removed and machine felled, whole-tree removed). Two other treatment factors at the Fred site were bedding (bedded and not bedded) and fertilization (or not). At Bryceland only one other factor was combined with harvesting: none, herbaceous weed control, and broadcast burning.

The Fred and Bryceland sites were planted in 1996 and 1997, respectively, and have been measured annually since. Annual quadratic mean diameter was calculated for each plot from the average basal area per tree. Annual diameter increment is the successive change in quadratic mean diameter. Relative density is calculated as the value of stand density index as a fraction of the maximum stand density index for loblolly pine noted by Reineke (1933). Stand density index is calculated with the equation $SDI=TPH(Dq/25)^{1.6}$, where TPH = trees/ha. Relative density is relative to a maximum SDI of 1110 for loblolly pine. Individual tree leaf area (A) was calculated with the equation $A = (0.0676+0.0463\ I)\ (dbh^{2.201})/(H^{0.135})$, where I=1 if fertilized, 0 otherwise; dbh=diameter at 1.37 m (cm); and H=total tree height (m). The height to median leaf area was assumed to be the midpoint of the live crown. The probability of making of Type I error was limited to 0.10.

RESULTS AND DISCUSSION

Quadratic Mean Diameter

Both fertilization at time of planting at the Fred site and herbaceous weed control at the Bryceland site significantly increased Dq though the magnitude of the effect is much larger with fertilization than with herbaceous weed control (fig. 4). The effect of herbaceous weed control at age 8 years was not statistically significant (P=0.12). Annual increment in Dq decreased with age regardless of treatment (fig. 5). Fertilization significantly increased Dq increment between ages 3 and 5 years; herbaceous weed control increased Dq increment only at ages 3 and 4 years.

Growth—Growing Stock Relations

Relative density did not account for the comparatively large effect of fertilization on relative differences in Dq

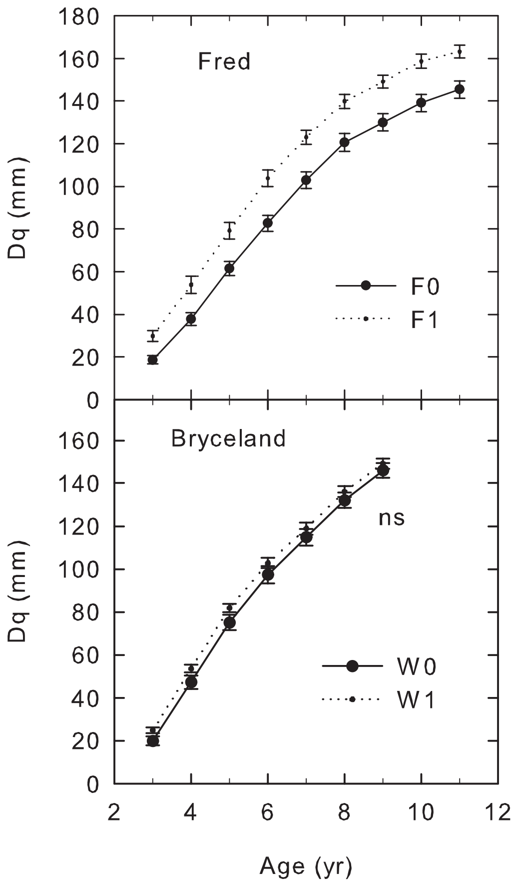

Figure 4—Effects of fertilization at time of planting (Fred) and herbaceous weed control (Bryceland) on chronology of quadratic mean diameter (Dq).

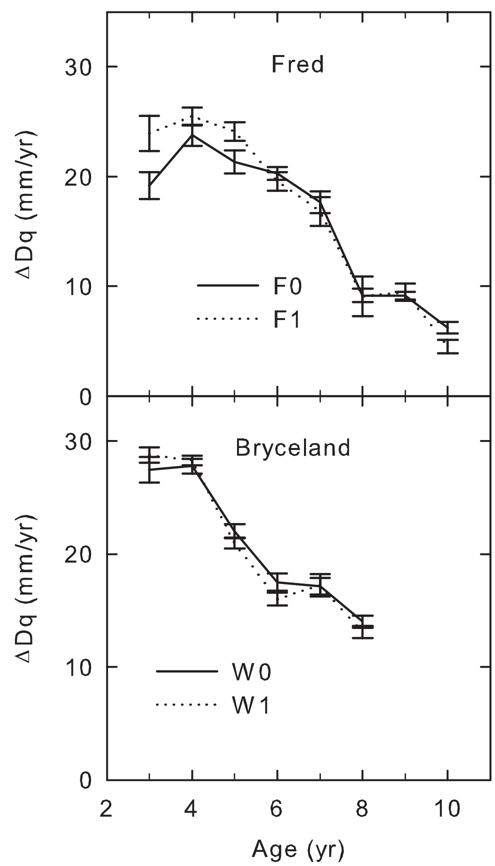

Figure 5—Effect of fertilization (Fred) and herbaceous weed control (Bryceland) on annual increment in Dq. Error bars are plus and minus one standard error.

increment (fig. 6). In other words, fertilization increased site occupancy without the expected commensurate reduction in relative increment in Dq. Relative density accounted for the small effect of herbaceous weed control on relative annual increment of Dq, especially at the young ages where herbaceous weed control significantly increased both diameter increment and SDI.

Accelerated Development

According to the accelerated development model, treatment effects, especially fertilization, should dissipate, returning growth to a value commensurate with its advanced stage of development. Miller (1981) implies that size manifests tree development, but offers no guidance on how to define size. Data from these plantations do not support this model, however. For a common initial value of leaf area per tree, fertilized trees exhibited greater diameter increment than unfertilized trees (fig. 7). At no time during this study did diameter increment of fertilized trees match the diameter increment of the unfertilized trees.

Tree Morphology

The morphological relationships between leaf area, its vertical distribution, and stem diameter appear to account for both the presence and absence of treatment effects on the annual increment of Dq in these loblolly pine trees (fig. 8). According to this model, larger annual increases in crown dimensions are required to produce the same diameter increment as the initial crown size is larger. The need to have larger increments in crown size to maintain constant values of diameter increment as the crown enlarges seems to account for the loss of significant fertilization effects on Dq after age 5 at the Fred site. This also seems to account for the lack of an effect of herbaceous weed control on Dq increment. While trees receiving early herbaceous weed control at the Bryceland site had larger crowns, the increment in crown size was only sufficient to maintain Dq increment at values similar to that observed with the unreleased trees.

ACKNOWLEDGMENTS

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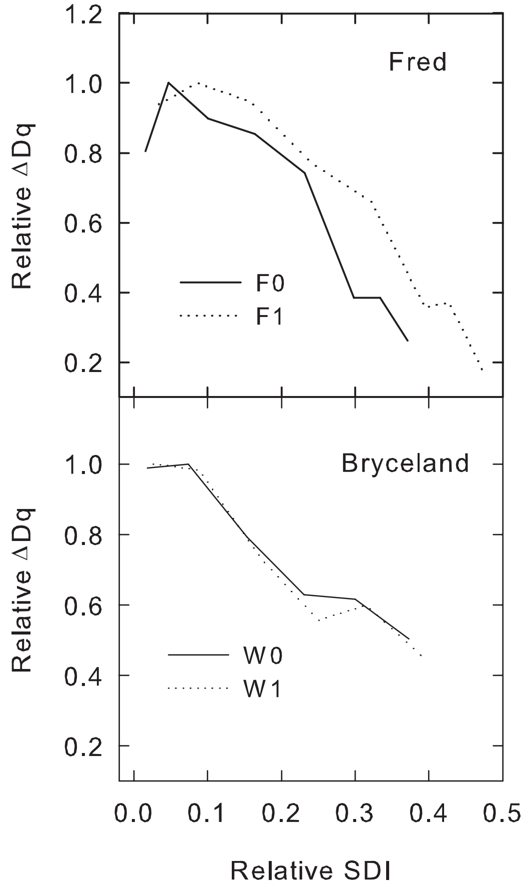

Figure 6—Effect of fertilization (Fred) and herbaceous weed control (Bryceland) on annual increment in quadratic mean diameter (Dq) relative to the maximum as a function of stand density index (SDI) relative to the maximum value for loblolly pine (450).

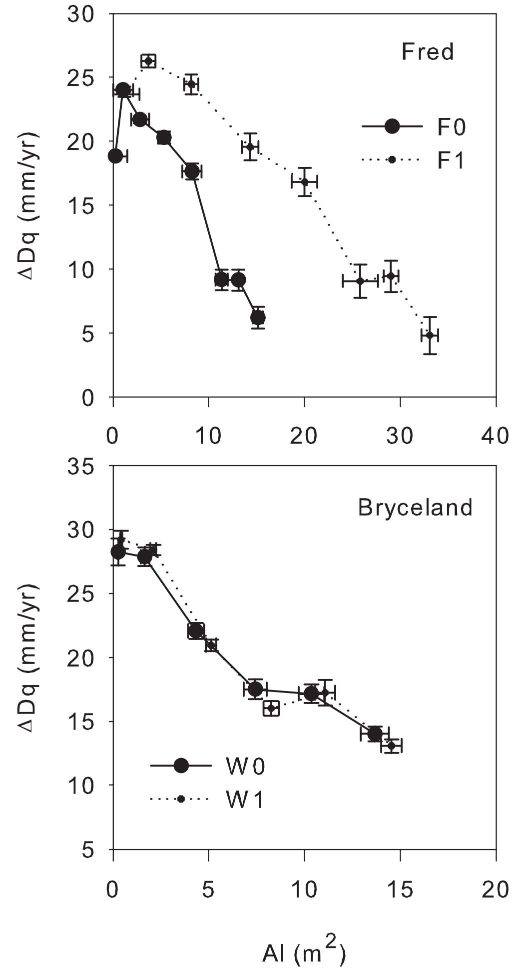

Figure 7—Effect of fertilization (Fred) and herbaceous weed control (Bryceland) on annual increment in mean quadratic diameters (ΔDq) and leaf area per tree (Al) at the beginning of the growing season. Vertical and horizontal bars are standard errors of the means.

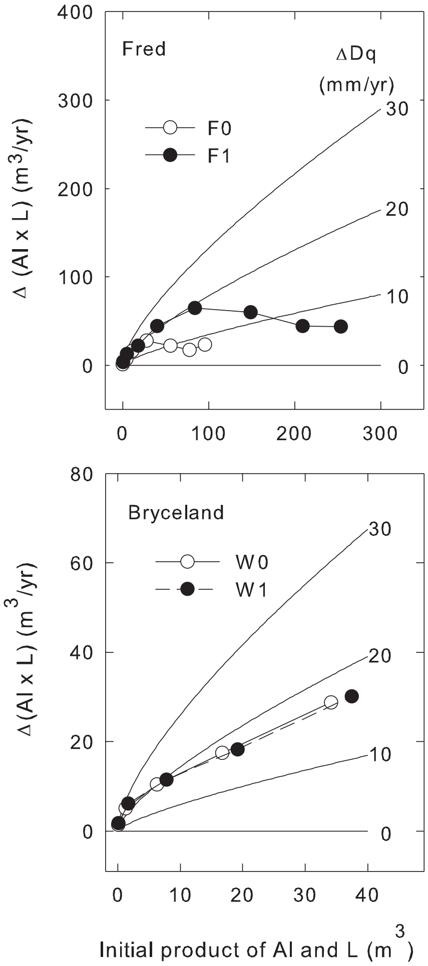

Figure 8—Isolines of annual increment in mean quadratic diameter (ΔDq) as a function of the average change in the product leaf area and distance between breast height and median leaf area and the average product of leaf area (ΔAl x L) and distance between breast height and median leaf area at the beginning of the growing season (Al x L). Plotted data are measured combinations of the (ΔAl x L) and (Al x L) of the treated and untreated plots at Fred, TX and Bryceland, LA, increasing in age from left to right.

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ADJUSTMENTS OF INDIVIDUAL-TREE SURVIVAL AND DIAMETER-GROWTH EQUATIONS TO MATCH WHOLE-STAND ATTRIBUTES

Quang V. Cao[1]

Abstract—Individual-tree models are flexible and can perform well in predicting tree survival and diameter growth for a certain growing period. However, the resulting stand-level outputs often suffer from accumulation of errors and subsequently cannot compete with predictions from whole-stand models, especially when the projection period lengthens. Evaluated in this study were five methods for adjusting the tree-survival equation to match observed number of trees per acre and three methods for adjusting the diameter-growth function to match observed basal area per acre. The evaluation procedures were repeated for adjustments using outputs from a whole-stand model. The different methods for adjusting tree survival probability and diameter growth were found to produce similar results. The methods selected (one for survival probability and another for diameter growth) both involved direct computation of the adjustment factor. Use of observed stand attributes for adjustment resulted in improvement of tree-level predictions of the individual-tree model. On the other hand, when predicted stand densities were used for adjustment, the quality of the tree-level predictions depended on the reliability of the stand predictions.

INTRODUCTION

Forest management decisions are based on information provided by growth and yield models, which ranged from simple whole-stand models, to size-class distribution models, and finally to complicated individual-tree simulation models. Each type of models has advantages and disadvantages; stand-level predictions from individual-tree and size-class models typically suffer from accumulation of errors, whereas whole-stand model outputs are often better behaved but lack information on stand structures (Qin and Cao 2006).

Attempts have been made to link models of different resolutions, such as diameter-distribution and whole-stand models (Baldwin and Feduccia 1987, Matney and Sullivan 1982), individual-tree and diameter-distribution models (Bailey 1980, Cao 1997, Qin and others 2007), stand-table projection and whole-stand models (Cao 2006, Nepal and Somers 1992, Pienaar and Harrison 1988), and individual-tree and whole-stand models (Harrison and Daniels 1988, McTague and Stansfield 1995, Richie and Hann 1997*a*). Ritchie and Hann (1997*b*) reviewed the disaggregative approach that uses information from an individual-tree model to distribute stand growth (obtained from a whole-stand model) among trees in the tree list.

The objective of this study was to evaluate different disaggregation methods for adjusting the individual-tree survival and diameter growth equations to match stand predictions from a whole-stand model.

DATA

Data used in this study were from the Southside Seed Source Study, which included 15 seed sources of loblolly pine (*Pinus taeda* L.) planted at 13 locations across 10 southern states (Wells and Wakeley 1966). Seedlings were planted at a 6 by 6 ft spacing. Each plot of size 0.04-acre consisted of 49 trees. Tree diameters and heights were measured at ages 10, 15, 20, and 25 years. A subset (100 five-year-growth periods) of the original data was randomly selected as the fit data set, to be used for fitting the models. The validation data set, which comprised another 100 growth periods, was randomly selected from the rest of the data. Summary statistics for the fit and validation data sets are shown in table 1.

MODELS

Parameters of the following whole-stand model were simultaneously obtained from the fit data set by use of the seemingly unrelated regression method (SUR) in the SAS MODEL procedure (SAS Institute Inc. 2000):

$$\hat{N}_2 = N_1 / [1 + \exp(16.3284 - 42.4435\ RS_1 - 0.2277\ H_1 - 0.0665\ N_1/A_1 + 50.2900/A_1)] \quad (1)$$
$$s_{y.x} = 99.31;\ R^2 = 0.882$$

$$\hat{B}_2 = B_1\ [1 + \exp(-3.3277 - 0.1790\ B_1/A_1 + 41.0543/A_1)] \quad (2)$$
$$s_{y.x} = 32.00;\ R^2 = 0.647$$

where

$\hat{N}_2$ and $\hat{B}_2$ = number of trees and basal area (square feet) per acre, respectively, at the end of the growth period (age A_2),
N_1 and B_1 = number of trees and basal area per acre, respectively, at the beginning of the growth period (age A_1),
H_1 = average height of the dominants and codominants at time 1, and
$RS_1 = (43{,}560/N_1)^{0.5}/H_1$ = relative spacing at age A_1.

The following individual-tree growth model was also derived from the fit data set:

$$\hat{p}_i = [1 + \exp(1.3586 - 0.0026\ N_1 + 0.0239\ B_1 - 0.7371\ d_{1i})] \quad (3)$$
$$-2\ \log L = 2212;\ AIC = 2214$$

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Table 1—Means (and standard deviations) of stand and tree variables in the fit and validation data sets

Age	Dominant Height (ft)	Number of trees per acre	Basal area (sq ft/acre)	Tree diameter (in)
Fit data set				
10	29.4 (4.8)	667 (383)	76.8 (40.1)	11.2 (3.3)
15	28.3 (15.9)	574 (348)	115.2 (50.9)	14.9 (4.1)
20	36.0 (19.9)	437 (206)	128.3 (44.0)	18.1 (4.7)
25	19.5 (2.5)	400 (230)	138.5 (59.3)	19.6 (5.1)
Validation data set				
10	28.0 (5.2)	777 (284)	83.9 (31.2)	10.9 (3.2)
15	27.8 (15.9)	667 (249)	132.3 (33.5)	14.8 (4.0)
20	33.7 (19.9)	499 (167)	146.5 (37.3)	18.1 (4.3)
25	19.7 (2.5)	485 (171)	169.0 (41.8)	19.7 (4.9)

$$\hat{d}_{2i} = d_{1i} + 6.0988\,(A_2/A_1)^{2.0214}\,N_1^{-1.0104}\,B_1^{-0.3168}\,d_{1i}^{1.5122} \quad (4)$$

$s_{y.x} = 0.47$; $R^2 = 0.947$

where

$\hat{p}_i$ = predicted probability that tree *i* will survive the growth period,

d_{1i} = diameter at breast height (d.b.h.) of tree *i* at age A_1, and

$\hat{d}_{2i}$ = diameter at breast height of tree *i* at age A_2.

ADJUSTMENTS

Described below are different methods to adjust the individual-tree survival and diameter growth equation to match estimates of number of trees and basal area per acre from the whole-stand model.

Survival Adjustment

Method 1—The adjusted tree survival probability was expressed as a power function of the unadjusted probability as follows:

$$p_i^* = \hat{p}_i^{\,\alpha}, \quad (5)$$

where α is the adjustment coefficient.

Method 2—Jin and Cao (2006) assumed proportional ratios of dead and alive probabilities in developing the following adjustment:

$$p_i^* = \frac{\hat{p}_i}{\hat{p}_i + \alpha\,(1 - \hat{p}_i)}. \quad (6)$$

Method 3—The tree survival equation 3 was simplified as:

$$p_i^* = [1 + \exp(\alpha - 0.7371\, d_{1i})]. \quad (7)$$

Method 4—Eq. 3 can also be rewritten as:

$$p_i^* = [1 + \exp(1.3586 - 0.0026\, N_1 + 0.0239\, B_1 + \alpha\, d_{1i})]. \quad (8)$$

In methods 1–4 above, SAS procedure MODEL (SAS Institute, Inc. 2000) was used to iteratively solve for the value of α for each plot such that $\Sigma p_i^* = s\hat{N}_2$. Note that eq. (5–8) are properly constrained, so that p_i^* is always between 0 and 1.

Method 5—The adjusted tree survival probability (p_i^*) was obtained from

$$p_i^* = \hat{p}_i + \alpha(1 - \hat{p}_i), \quad (9)$$

where

$\alpha = \dfrac{s\hat{N}_2 - \Sigma\hat{p}_i}{n_1 - \Sigma\hat{p}_i}$ = adjustment coefficient,

s = plot size in acres,

$\hat{N}_2$ = number of trees per acre at the end of the growth period as predicted from the whole-stand model,

n_1 = number of trees in a plot at the beginning of the period, and the summation signs include values of *i* from 1 to n_1.

Equation 9 has an upper asymptote of 1, but p_i^* could be negative. The latter case occurs when the value of Σp_i is too high compared to $s\hat{N}_2$. It was necessary in this case to employ a two-step procedure as follows:

1. In the first step, the survival probability was adjusted using eq. 9 such that the probability for the smallest diameter (d_{min}) in the plot equaled zero. Let p_{min} be the unadjusted survival probability, computed from eq. 3, of the tree with the smallest diameter. Let α_{min} be the value of α such that the adjusted survival probability from this step equaled zero for the smallest diameter. In other words, α_{min} is the solution of:

$$p_{min} + \alpha_{min}\,(1 - p_{min}) = 0, \text{ or } \alpha_{min} = -p_{min}/(1 - p_{min}). \quad (10)$$

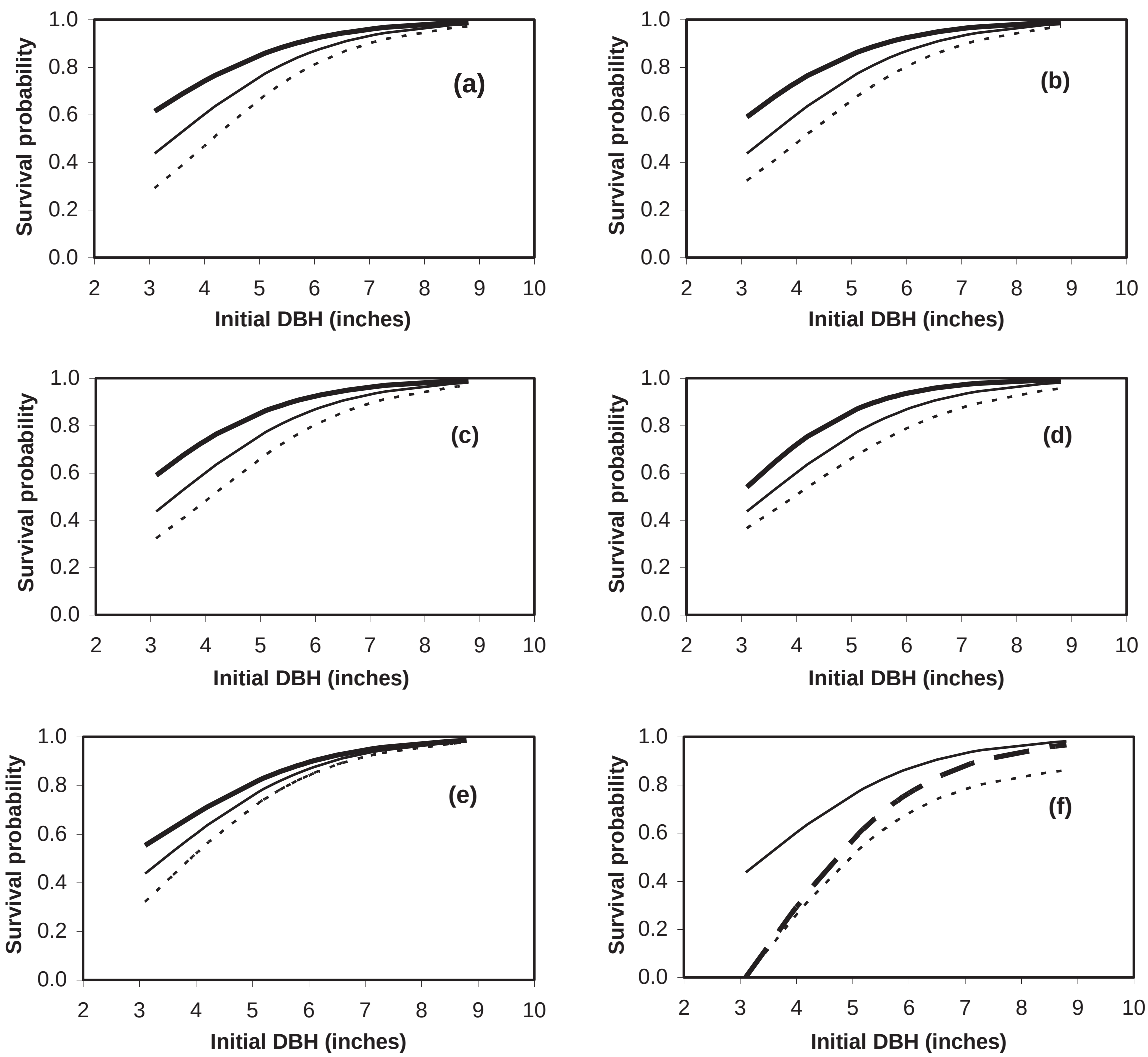

Figure 1—Figures (a) to (e) illustrate, respectively, methods 1 to 5 of adjusting tree survival probability. The unadjusted survival probability (thin solid line) is adjusted upwards (bold solid line) to increase the predicted stand density by 10 percent, or downwards (dotted line) to decrease the predicted stand density by 10 percent. Figure (f) demonstrates the case when the adjustment in method 5 needs to be done in two steps. The survival probability is adjusted downwards (dashed line) using Eq. (9) in the first step to zero probability for the smallest diameter, then downwards further (dotted line) using Eq. (11) in the second step.

2. In the second step, the final probability was proportional to the adjusted survival probability from step 1:

$$p_i^* = \beta\,[\,\hat{p}_i + \alpha_{min}(1 - \hat{p}_i)],$$

$$\text{where } \beta = \frac{s\hat{N}_2}{\Sigma\hat{p}_i + \alpha_{min}(n_1 - \Sigma\hat{p}_i)} \qquad (11)$$

The five methods for adjusting tree survival probability are illustrated in figures (1a–1f).

Diameter Growth Adjustment

Method 1—The tree diameter growth eq. 4 can be simplified by using α to express the effect of stand attributes:

$$d_{2i}^* = d_{1i} + \alpha\, d_{1i}^{1.5122} \qquad (12)$$

Method 2—The power for d_{1i} in Equation 4 was replaced with the adjustment coefficient (α) as follows:

$$d_{2i}^* = d_{1i} + 6.0988\,(A_2/A_1)^{2.0214}\,N_1^{-1.0104}\,B_1^{-0.3168}\,d_{1i}^{\alpha} \qquad (13)$$

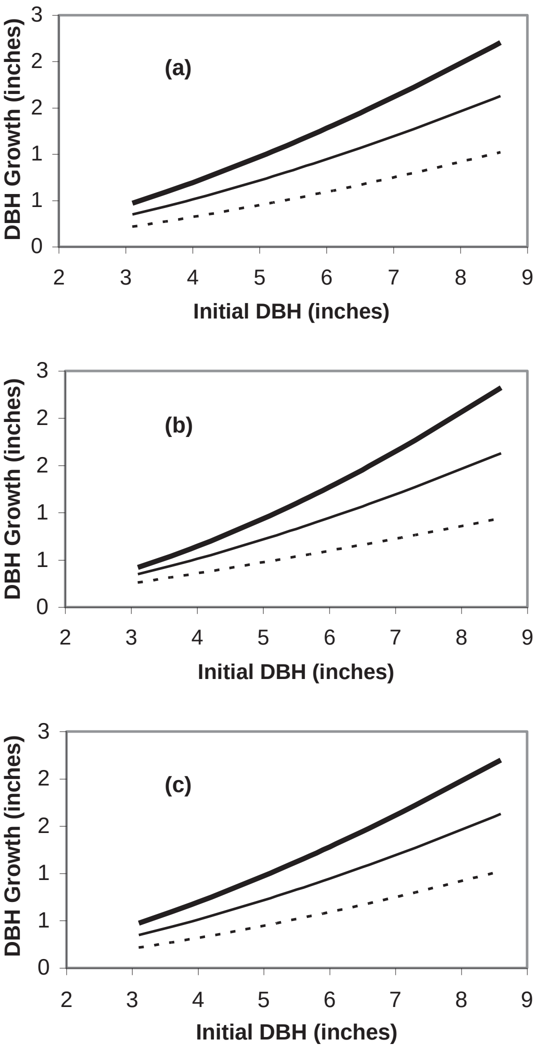

Figure 2—Figures (a) to (c) illustrate, respectively, methods 1 to 3 of adjusting tree diameter growth rate. The unadjusted diameter growth (thin solid line) is adjusted upwards (bold solid line) to increase the predicted stand basal area by 10 percent, or downwards (dotted line) to decrease the predicted stand basal area by 10 percent.

In methods 1 and 2 above, the value of α for each plot was iteratively determined such that $K \Sigma p_i^* d_{2i}^{*2} = s\hat{B}_2$, where K = 0.005454.

Method 3—The adjusted squared diameter growth of each tree was assumed to be proportional to the predicted squared diameter growth, leading to:

$$d_{2i}^{*2} = d_{1i}^2 + \alpha\,(\hat{d}_{2i}^{\,2} - d_{1i}^2),$$

$$\text{where } \alpha = \frac{(s\hat{B}_2 / K - \Sigma(p_i^* d_{1i}^2)}{\Sigma[\,p_i^*(\hat{d}_{2i}^2 - d_{1i}^2)]} \quad (14)$$

Figures (2a–2c) illustrate the three methods for adjusting tree diameter growth.

RESULTS AND DISCUSSION

The validation data set was employed to evaluate the unadjusted and adjusted methods for predicting tree survival probability and diameter growth. The individual-tree equations were adjusted with observed and then predicted number of trees and basal area per acre. Common evaluation statistics for both tree survival probability and diameter growth included mean difference (MD) between observed and predicted values, and mean absolute difference (MAD).

Survival Adjustment

In addition to MD and MAD, –2ln(*L*) was added as the third evaluation statistic, where *L* is the likelihood function. All of the adjustment methods provided better evaluations statistics than did the unadjusted probabilities (table 2), whether the stand attributes used for adjustment were observed or predicted from the whole-stand model. The five adjustment methods were comparable, producing similar evaluation statistics. The first four methods required the adjustment coefficient, α, to be solved in an iterative manner, whereas method 5 allowed α to be directly computed. Therefore method 5 was selected as the appropriate method for adjusting tree survival probability.

Use of observed stand attributes for adjustment greatly reduced the MD value, compared with the unadjusted model, from 0.0250 to almost zero, MAD from 0.2483 to 0.1832, and –2ln(*L*) from 2030 to 1475 for method 5. As expected, predicted stand attributes did not fare as well; the evaluation statistics for method 5 were –0.0168, 0.2146, and 2012 for MD, MAD and –2ln(*L*), respectively. These statistics were, however, still better than those from the unadjusted method. It was clear from these results that the success of the adjustment largely depended on the quality of the stand predictions.

Table 2—Evaluation statistics† for the unadjusted and adjusted predictions of tree survival probability from the validation data set

Method	MD	MAD	-2 ln(*L*)
Unadjusted	0.0250	0.2483	2030
Adjusted from observed stand attributes			
Method 1	0.0000	0.1812	1486
Method 2	0.0000	0.1866	1469
Method 3	0.0000	0.1834	1486
Method 4	0.0000	0.1844	1486
Method 5	0.0000	0.1832	1475
Adjusted from predicted stand attributes			
Method 1	–0.0168	0.2148	2015
Method 2	–0.0168	0.2331	1977
Method 3	–0.0168	0.2147	2013
Method 4	–0.0168	0.2142	2098
Method 5	–0.0168	0.2146	2012

† MD = mean difference between observed and predicted probabilities, MAD = mean absolute difference, and *L* = likelihood function.

Diameter Growth Adjustment

The survival probability adjusted with method 5 above was used in conjunction with the three methods for adjusting tree diameter growth to match stand basal area. The evaluation statistics employed for this purpose were MD, MAD, and fit index (FI), which is computationally similar to R^2 in linear regression.

The three adjustment methods resulted in similar evaluation statistics (table 3). The adjustment coefficient, α, was directly computed in method 3, but had to be iteratively searched in the first two methods. Therefore method 3 was selected as appropriate for adjusting tree diameter growth. When observed values of number of trees and basal area per acre were used for adjustment, the resulting future diameters from method 3 produced a higher MD value (0.0589 vs. 0.0421) than the unadjusted, but lower MAD (0.3383 vs. 0.3765) and higher R^2 (0.9464 vs. 0.9368). If predicted tree survival probability was further replaced with observed survival in the diameter adjustment process, the results improved to –0.0132 for MD and 0.9537 for R^2. The adjustment for diameter growth thus was partly influenced by how accurate the survival prediction was.

When diameter growth was adjusted using predicted stand densities, MD improved to 0.0332, but MAD and R^2 deteriorated to 0.4258 and 0.9211, respectively, which were even worse than those from the unadjusted method. The reason might be traced to the lack of accuracy and precision in predicting stand basal area, as evidenced in a fairly low R^2 (0.647).

SUMMARY AND CONCLUSIONS

In this study, the different methods for adjusting tree survival probability and diameter growth were found to produce similar results. The methods finally selected (method 5 for survival probability and method 3 for diameter growth) both involved direct rather than iterative computation of the adjustment coefficient (α). Use of *observed* stand attributes for adjustment resulted in improvement of tree-level predictions of the individual-tree model. On the other hand, when *predicted* stand densities were used for adjustment, the quality of the tree-level predictions depended on the reliability of the stand predictions.

Table 3—Evaluation statistics† for the unadjusted and adjusted predictions of tree diameter growth from the validation data set

Method	MD	MAD	FI
Unadjusted	0.0421	0.3765	0.9368
Adjusted from observed stand attributes			
Method 1	–0.0589	0.3384	0.9463
Method 2	–0.0630	0.3385	0.9462
Method 3	–0.0590	0.3383	0.9464
Adjusted from predicted stand attributes			
Method 1	0.0332	0.4258	0.9211
Method 2	0.0328	0.4274	0.9200
Method 3	0.0332	0.4258	0.9211

† MD = mean difference between observed and predicted values, MAD = mean absolute difference, and FI = fit index, computationally similar to R^2 in linear regression.

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COMPATIBLE TAPER AND VOLUME EQUATIONS FOR YOUNG LONGLEAF PINE PLANTATIONS IN SOUTHWEST GEORGIA

Lichun Jiang, John R. Brooks, and Alexander Clark III[1]

Abstract—Inside and outside bark taper equations as well as compatible cubic foot volume equations were developed from felled tree data selected from young longleaf pine plantations that are part of an existing growth and yield study located in the Flint River drainage of southwest Georgia. A Max-Burkhart taper model was selected as the basic model form due to the accuracy found when applied to other southern pine species. Average diameter prediction error was approximately 0.25 inch and volume prediction error was less than 0.032 cubic feet.

INTRODUCTION

Taper and volume functions have been published for outside bark diameters (Baldwin and Polmer 1981) and inside bark diameters (Thomas and others 1995) for longleaf pine (*Pinus palustris* Mill.) plantations in central LA and east TX. Total and merchantable cubic foot volume equations have also been developed for plantations in this same region by Baldwin and Saucier (1983). Most published mensurational information on planted longleaf stands has been for cutover sites in the West Gulf physiographic region. Little is known regarding the growth and yield of longleaf plantations in southeast Georgia, especially for more intensively managed stands. Brooks and others (2002) presented an outside bark taper and a compatible cubic foot volume equation for young longleaf plantations in the southeast GA. The resultant taper equation was superior to the published equation by Baldwin and Polmer (1981). The resultant volume equation also showed more accurate volume estimates for this GA data set than equations published by Baldwin and Polmer (1981) or Baldwin and Saucier (1983).

The objective of this study was to develop inside and outside bark compatible taper and cubic foot volume equations as part of a growth and yield study for unthinned longleaf pine plantations on cutover sites in Southwest GA. Preliminary outside bark taper and volume equations based on the data used for the model developments discussed herein were published earlier (Brooks and others 2002).

DATA

Sample trees were selected during the summer of 2000 from three unthinned plantations in Dougherty and Worth Counties, GA that are part of an existing growth and yield study. Plantations were established in cutover stands that received mechanical as well as chemical site preparation. Plantations ranged in age from 12 to 14 years and were established on sandy loam soils using bare root seedlings. Approximately 15 sample trees were selected from the interior of each plantation from the area buffering existing permanent growth and yield plots. Trees possessing multiple stems, broken tops, obvious cankers or crooked boles were not included in the sample. Each sample tree selected for stem analysis was felled at ground level. A 100-foot tape was used to directly measure total height of each tree following felling (recorded to the nearest 0.1 foot). Diameter outside bark (d.o.b.) at breast height was measured and recorded to the nearest 0.1 inch. Each tree was bucked into sections and one inch thick sample disks were obtained at different heights above the tree base. Disks were extracted at the base, 0.5, 2.0, 4.5, 6.0 feet and at 4 foot intervals to a two-inch top diameter outside bark. Each disk was labeled and sealed in a plastic bag to preserve moisture and prevent shrinkage. In the laboratory, diameter outside and inside bark of each disk were measured. The data set included 420 inside and outside bark measurements on 42 sample trees. Actual volume for each bolt and tree was calculated using the overlapping bolts method as described by Bailey (1995) and a generalized Newton formula described by Wiant and others (1992). Sample tree distribution by height and diameter class is displayed in table 1.

TAPER AND VOLUME EQUATION

The Max and Burkhart (1976) segmented polynomial taper equation was selected for use in this study. This equation is well-known and widely used in the United States. This equation is of the form:

$$\frac{d^2}{D^2} = b_1(Z-1) + b_2(Z^2-1) + b_3(a_1-Z)^2 I_1 + b_4(a_2-Z)^2 I_2 \qquad (1)$$

Table 1—Distribution of sample trees by d.b.h. and total height class

d.b.h. class (in)	Total height class (ft) 20	25	30	35	40	Totals
2	5	3				8
3		4	1			5
4		2	5	5		12
5			1	4	2	7
6				5	1	6
7				1	3	4
Totals	5	9	7	15	6	42

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where:

$$I_i = \begin{cases} 1 & Z \le a_i \\ 0 & Z > a_i \end{cases} \qquad i = 1, 2$$

$Z = h/H$

h = height above the ground to the measurement point (feet),

H = total tree height (feet),

D = diameter outside bark at breast height (inches),

d = diameter outside bark to measurement point at height h (inches),

a_i = join points to be estimated from the sample data.

$i = 1, 2$,

b_1, b_2, b_3, b_4 : regression coefficients.

A volume equation was derived by integrating the Max and Burkhart taper equation:

$$kD^2H \begin{Bmatrix} \frac{b_2}{3}(Z_u^3 - Z_l^3) + \frac{b_1}{2}(Z_u^2 - Z_l^2) - (b_1 + b_2)(Z_u - Z_l) \\ -\frac{b_3}{3}[(a_1 - Z_u)^3 J_1 - (a_1 - Z_l)^3 K_1] \\ -\frac{b_4}{3}[(a_2 - Z_u)^3 J_2 - (a_2 - Z_l)^3 K_2] \end{Bmatrix} \qquad (2)$$

where:

k = 0.0054542,

$Z_l = h_l/H$,

$Z_u = h_u/H$,

h_l = lower height of interest (feet),

h_u = upper height of interest (feet),

$$J_i = \begin{cases} 1 & Z_u \le a_i \\ 0 & Z_u > a_i \end{cases} \qquad i = 1, 2$$

$$K_i = \begin{cases} 1 & Z_l \le a_i \\ 0 & Z_l > a_i \end{cases} \qquad i = 1, 2$$

All other variables as previously defined.

MODEL EVALUATION

To evaluate model performance, average bias, the standard error of the estimate and a fit index, as described by Schlaegel (1981), were employed for model evaluation. These evaluation statistics are defined as:

$$Average\ Bias = \frac{\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)}{n}$$

$$SEE = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2}{\text{n-k}}}$$

$$FI = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2}{\sum_{i=1}^{n}\left(Y_i - \bar{Y}\right)^2}\right]$$

where:

Y_i = observed value for the i[th] observation,

$\hat{Y}_i$ = predicted value for the i[th] observation,

$\bar{Y}$ = mean of the Y_i,

k = the number of estimated parameters,

n = number of observations in the dataset,

SEE = the standard error of the estimate,

F = fit index.

To concurrently minimize error in compatible taper and volume, the taper and volume equations were fitted simultaneously using SUR procedure in SAS (SAS Institute 2002). All parameters were shared by both the taper and volume equations. The models were independently fitted to both outside and inside bark data.

RESULTS

Taper Equation

Parameter estimates were obtained by simultaneously fitting the taper and volume equations (outside bark and inside bark). All parameters in the equation were found to be significant at the 0.0001 level (tables 2 and 3). The overall statistics of fit (average bias, SEE and FI) for the entire merchantable stem were calculated and presented in table 4 for both diameters outside and inside bark. The results indicate that equation 1 explained more than 97 percent of the variation in diameter outside and inside bark. Equation 1 was further evaluated by relative height (h/H) classes in order to evaluate its performance at different positions throughout the merchantable stem. Since stem analysis was stopped at a 2-inch top diameter outside bark, the data were split into nine relative height classes. Average bias and SEE were calculated for each equation by relative height class and used to evaluate taper and volume (outside bark and inside bark) estimates (table 5). The results indicate that equation 1 performed well for all sections. Average error (SEE) ranged from 0.2 to 0.3 inch for diameter outside and inside bark.

Volume Prediction

Statistics of fit (average bias, SEE and FI) for the entire merchantable stem volume (outside and inside bark) are presented in table 4. Equation 2 explained more than 96 percent of the variation for predicting volume outside and inside bark. The results indicate that equation 2 had better overall prediction statistics for volume with lower average biases, SEE and higher FI. Volume prediction by relative height class was also evaluated (table 5). Equation 2 performed well for all sections. Average error (SEE) ranged from 0.016 to 0.042 cubic feet for volume outside bark and between 0.013 and 0.034 cubic feet for volume inside bark.

Table 2—Parameter estimates, standard errors and *P*-values for planted longleaf pine outside bark taper and volume equations

Parameter	Estimate	Standard Error	*P*-value
b_1	-2.7307	0.3314	<0.0001
b_2	1.1566	0.1935	<0.0001
b_3	-0.7712	0.1828	<0.0001
b_4	380.9826	61.5103	<0.0001
a_1	0.6457	0.0823	<0.0001
a_2	0.0339	0.0026	<0.0001

Table 3—Parameter estimates, standard errors and *P*-values for planted longleaf pine inside bark taper and volume equations

Parameter	Estimate	Standard Error	*P*-value
b_1	-2.4164	0.2037	<0.0001
b_2	1.0841	0.1204	<0.0001
b_3	-1.2913	0.1187	<0.0001
b_4	235.6075	56.9886	<0.0001
a_1	0.6047	0.0396	<0.0001
a_2	0.0373	0.0043	<0.0001

Table 4—Fit statistics of each equation in the taper and volume equations

Equation	Avg. Bias	SEE	FI
Dob	0.0455	0.2633	0.9723
V_{ob}	0.0041	0.0311	0.9664
Dib	-0.0010	0.2301	0.9726
V_{ib}	0.0020	0.0244	0.9651

V_{ob} *= volume outside bark*
V_{ib} *= volume inside bark*

Table 5—Bias and standard error of the estimate by relative height (RH) class for the inside and outside bark taper and volume equations

		Dob (in)		V_{ob} (ft³)		Dib (in)		V_{ib} (ft³)	
RH	n	Bias	SEE	Bias	SEE	Bias	SEE	Bias	SEE
0.0-0.1	121	0.069	0.290	0.004	0.016	-0.009	0.248	0.003	0.013
0.1-0.2	65	-0.054	0.173	-0.005	0.033	-0.048	0.167	-0.001	0.025
0.2-0.3	39	0.053	0.205	0.009	0.040	-0.012	0.188	0.003	0.033
0.3-0.4	30	0.035	0.234	0.007	0.032	0.025	0.224	0.003	0.024
0.4-0.5	51	0.070	0.313	0.006	0.042	0.031	0.268	0.002	0.034
0.5-0.6	37	0.083	0.308	0.006	0.041	0.023	0.251	0.002	0.032
0.6-0.7	33	0.040	0.323	0.002	0.041	0.008	0.299	0.000	0.033
0.7-0.8	31	0.056	0.298	0.008	0.026	0.010	0.253	0.004	0.019
0.8-0.9	13	0.111	0.248	0.013	0.020	0.036	0.202	0.008	0.014

CONCLUSIONS

In this study, a system of taper and volume equations were developed for young longleaf pine in southwest GA. To ensure numeric consistency, a simultaneous fitting procedure was used. Parameter estimates were obtained that simultaneously minimized taper and volume error. Equations 1 and 2 showed consistent performance in terms of overall fit statistics, sectional performance, average bias and SEE in estimating diameter and volume, respectively. In the future, weight equations (green wood and bark, green wood, dry wood) will be developed using density-integral approach and compatible taper, volume and weight equations system will be derived.

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APPLYING THE AGE-SHIFT APPROACH TO MODEL RESPONSES TO MIDROTATION FERTILIZATION

Colleen A. Carlson, Thomas R. Fox, H. Lee Allen, and Timothy J. Albaugh[1]

Abstract—Growth and yield models used to evaluate midrotation fertilization economics require adjustments to account for the typically observed responses. This study investigated the use of age-shift models to predict midrotation fertilizer responses. Age-shift prediction models were constructed from a regional study consisting of 43 installations of a nitrogen (N) by phosphorus (P) factorial experiment established in midrotation loblolly pine stands in the Southeast United States. Ten years of data indicated that, with time after fertilization, the age-shifts increased to an asymptote. The asymptote and the time to reach it were functions of the rate of fertilizers applied, as well as initial stand parameters including initial stocking, dominant height, stand age and basal area. The methodology was verified with an independent data set.

INTRODUCTION

Midrotation fertilization responses need to be included in growth and yield models in order to make economic analyses and predict stand yield. Approaches used to model midrotation fertilization responses have included adjusting site index (SI) (Daniels and Burkhart 1975), adding a term associated with the response to a yield function (Amateis and others 2000, Pienaar and Rheney 1995), using a multiplier to adjust the growth rate of the trees according to the elements (both rate and form) that were applied (Hynynen and others 1998), or "hard wiring" the fertilizer response into the growth and yield model (Bailey and others 1989, Martin and others 1999). We investigated the use of age-shifts to model midrotation fertilizer responses.

Miller and Cooper (1973) originally suggested that midrotation fertilizer responses are analogous to stand development acceleration through time. Midrotation applications of N and P generally result in Type B responses (Nilsson and Allen 2003) in the Southeastern United States (Fox and others 2007). That is, the growth rate of the treated trees increases relative to the untreated ones for a short period of time, after which all trees have similar growth trajectories. Consequently the treated trees reach a given height, diameter or volume earlier, thus reducing the rotation length. These responses are compatible with the age-shift concept. The age-shift approach has been used to evaluate various silvicultural treatments (Kimberley and others 2004, Lauer and others 1993, Snowdon 2002, South and others 2006), and the methodology for calculating age-shifts has been discussed extensively by South and others (2006). The aim of the current study was to use this approach on data from two regional fertilizer trial series.

METHODS

Data from the Forest Nutrition Cooperative's Regionwide 13 trial series were used to construct age-shift prediction models. The Regionwide 13 study was a four (0, 100, 200, and 300 pounds-N/acre applied as urea [46 percent]) by three (0, 25, and 50 pounds-P/acre applied as triple superphosphate (20 percent)) factorial experiment replicated two or four times in 43 midrotation loblolly (*Pinus taeda*) stands aged between 9 and 19 years. Data used to validate the model was from the Forest Nutrition Cooperative's Regionwide 15 trial series which consisted of three or four replicates of a variable treatment matrix that included two treatments (an untreated control and 200 pounds-N/acre applied with 50 pounds-P/acre) common to the Regionwide 13 trials and had been established in stands aged between 11 and 25 years.

Age-shifts were determined using the basal area mean response for each treatment at each site. The response was defined as the difference in basal area at a particular time after fertilization and the value prior to fertilization. The age-shift was calculated by regressing control plot basal area against years since fertilization. The fertilizer response data was then substituted into the derived regression equation in order to estimate the time required for an untreated stand to grow to the equivalent basal area. Finally, the age-shift was calculated by subtracting the number of years since fertilization from the estimated time required to reach that level of basal area. The shapes of the fertilized and control treatment responses were verified as being similar. This is a critical assumption of the methodology.

A model was constructed to predict the Regionwide 13 basal area age-shifts based on the time since fertilization, the treatments, and the initial stand parameters. This model was then used to predict the age-shift associated with basal area for the Regionwide 15 data set. The correlation between the actual age-shift and the predicted age-shift in the Regionwide 15 data was examined with the Pearson correlation coefficient. The difference between the actual age-shift in the Regionwide 15 data set and the predicted age-shift based was then calculated. This difference was subject to a t-test, with the null hypothesis being that the difference should be zero. This would be the case if the model predicted 100 percent accurately.

All statistical and data analyses were performed using SAS (SAS Institute 2005).

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RESULTS AND DISCUSSION

The mean basal area age-shifts determined from the Regionwide 13 data for each treatment combination are shown in figure 1. When both N and P are applied, the age-shifts increase to an asymptote as the time after fertilization increases, and the magnitude of the asymptote and the time to reach it are functions of the applied nutrients and the application rate. Where no P was applied, the age-shift is transient, peaking at a lower level, and then decreasing. The age-shift data shows little response to P alone, but an increasing response to increasing rates of N, with significantly larger responses when 200 or 300 pounds/acre of N is applied in the presence of P. This is similar to reports in the literature (Amateis and others 2000, Hynynen and others 1998). However, there is little difference in response when P is applied at 25 or 50 pounds/acre.

The basal area age-shifts calculated from the two different trial series for the 200 pounds-N/acre plus 50 pounds-P/acre treatment follow the same trend over time (table 1). There were no significant differences in the estimates made from the different data sets within a given time period indicating the robustness of the technique.

The model that was derived from the Regionwide 13 is given below (parameter estimates in table 2).

$$\text{basal area} = d_0.e^{(1-(d5*Nrate))}.(YST^{d1}).e^{(YST.(d2+(d3*Pindi)))}.(TPA0/1000)^{d4}.(Ht_{dom0}/age0)^{d6} \quad (1)$$

where:

basal area is the age-shift for basal area; N rate is the rate of N application (pounds/acre); YST is the years since application; Pindi is an indicator variable where 1 denotes that P was applied and 0 elsewhere; and TPA0, Ht_{dom0}, and age0 are respectively, the trees per acre, dominant height (feet), and age at time of fertilization.

Two Regionwide 15 studies were poorly predicted by the derived model. These studies had shown unusually large gains from fertilization with a 53 and 70 percent improvement in basal area which equated to an age-shift of 5.22 and 7.33 years respectively. These results indicate a Type A response to the fertilizer application which apparently changed the carrying capacity of the site. When excluding these two studies in the basal area predictions, a significant ($p<0.0001$) Pearson correlation coefficient of 0.74 was found between the predicted and the actual age-shifts.

The mean difference between the actual age-shift in the Regionwide 15 data set and the predicted age-shift based on the model was determined to be -0.10 years. The null hypothesis from the t-test was rejected indicating that the model significantly over-predicted basal area. Although the margin of over-prediction was small, it indicates that further model refinement is necessary.

CONCLUSIONS

We conclude that the use of the age-shift approach is a viable option for modeling midrotation fertilizer responses. The age-shift can be included in stand level projection functions by simply adding the relevant age-shift to the projected age. The approach can be considered to have biological meaning if one considers that the response to the midrotation application of N and P accelerates stand development. The fact that the age-shifts can readily be

Table 1—Comparisons of the basal area age-shifts calculated from the Regionwide 13 and 15 trial series for the 200 pounds-N/acre plus 50 pounds-P/acre treatment

Years since treatment	Regionwide 13 Mean	Regionwide 13 95 % confidence limits		Regionwide 15 Mean	Regionwide 15 95 % confidence limits	
2	0.76 (n=43)	0.60	0.92	0.91 (n=24)	0.61	1.22
4	1.41 (n=38)	0.97	1.86	1.73 (n=23)	1.24	2.21
6	1.85 (n=31)	1.16	2.54	1.96 (n=16)	1.08	2.83
8	2.17 (n=25)	1.39	2.95	2.28 (n=13)	1.00	3.55
10	2.09 (n=19)	0.94	3.25			

The number of observations is given in parentheses adjacent to the mean.

The 95% confidence intervals indicate that there are no significant differences between the age-shifts associated with the different data sets at each time point. The shaded cells indicate that there was insufficient data to construct a confidence interval (i.e., n < 2).

Table 2—Parameter estimates for the model

Parameter	Estimate	Approx Standard Error	Lower CL	Upper CL
d0	0.0383	0.00676	0.025	0.0515
d1	1.7701	0.2285	1.3219	2.2184
d2	-0.3852	0.0449	-0.4733	-0.2971
d3	0.1404	0.015	0.111	0.1698
d4	0.7328	0.0798	0.5764	0.8893
d5	-0.00386	0.000244	-0.00433	-0.00338
d6	-0.7646	0.2531	-1.261	-0.2682

CL = 95 % confidence limits.

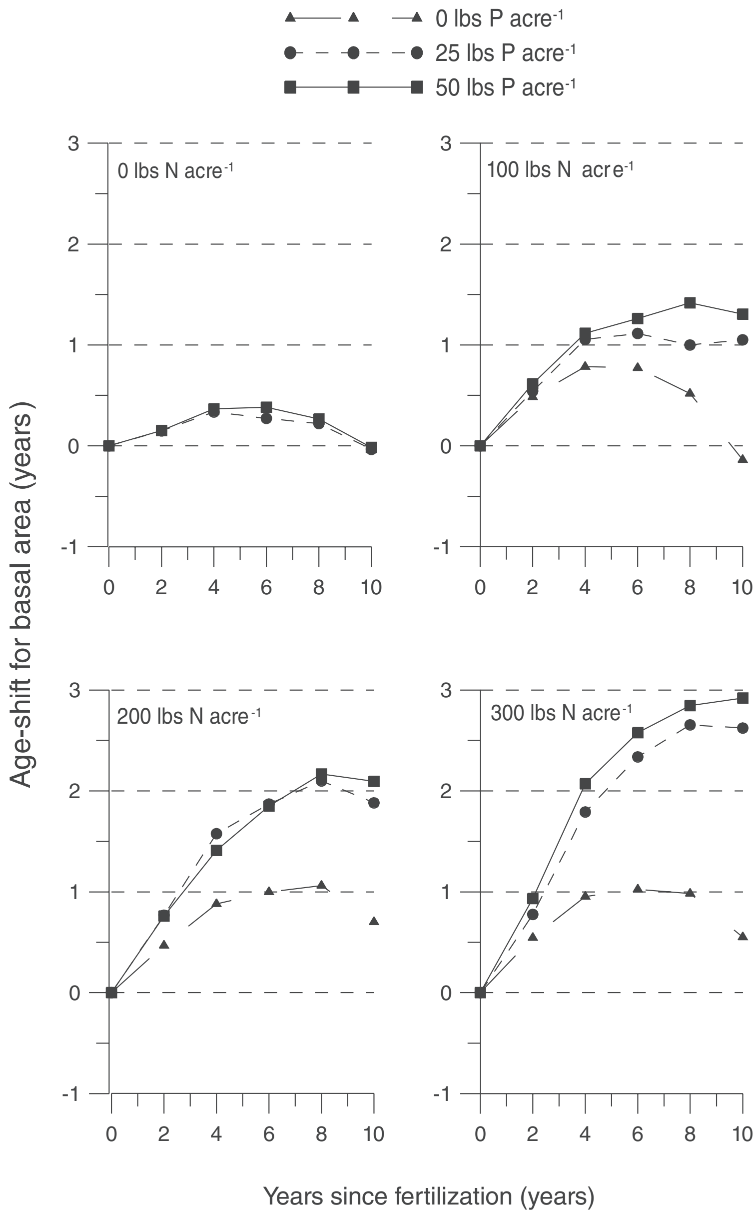

Figure 1—Age-shifts determined for basal area from the Regionwide 13 data. The four graphs show the age-shifts for 0, 100, 200, and 300 pounds/acre N respectively and on each graph the age-shift resulting from 0, 25, and 50 pounds/ acre P added with the respective N application is given.

incorporated into existing regional and company-specific growth and yield models indicates a degree of transferability in the technique that makes it attractive. Further work should focus on incorporating site-specific factors such as leaf area and growth efficiency, rather than stand specific parameters (e.g., age and stocking) into the model. In addition, future work needs to identify differences in response due to age-shifts, as opposed to changes in site quality which will allow distinction between Type B and A responses.

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ADJUSTING SITE INDEX AND AGE TO ACCOUNT FOR GENETIC EFFECTS IN YIELD EQUATIONS FOR LOBLOLLY PINE

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Abstract—Nine combinations of site index curves and age adjustments methods were evaluated for incorporating genetic effects for open-pollinated loblolly pine (*Pinus taeda* L.) families. An explicit yield system consisting of dominant height, basal area, and merchantable green weight functions was used to compare the accuracy of predictions associated with type of adjustment. Site index was adjusted by including height-age curves developed for the check family, all improved families combined, and for specific families. Age was adjusted by using a variant of the Pienaar and Rheney (1995) function. Age adjustments included none, all improved families combined, and for specific families. The best results were obtained by using height-age curves for all improved families combined and a family-specific age adjustment function. These results suggest that adjusting either site index alone or age alone is not sufficient for predicting the yield of genetically improved loblolly pine families planted in single-family blocks.

INTRODUCTION

Despite the need for forest growth models that include genetic effects in loblolly pine (*Pinus taeda* L.), few such models have been developed. Data from seed source and progeny tests generally are not suitable for model development because the linear arrangement of families in rows does not represent competition in stands. In addition, the type and method of genetic selection has progressed rapidly from seed sources, half-sib open-pollinated families, full-sib controlled mass pollinated families, clones obtained through rooted cuttings, and finally clones obtained by somatic embryogenesis.

Generally, growth models with interrelated components have been used to account for genetic differences. Only one function may need to be modified in order to incorporate genetic differences in growth models with interrelated components, whereas several functions may need to be modified in growth models with unrelated component equations (Burkhart and Matney 1981). As a result, research has focused on incorporating genetic differences into height-age functions (Buford and Burkhart 1987, Cao and Durand 1991a, Knowe and Foster 1989, Knowe and others 1998, Nance and Wells 1981, Sprinz and others 1987) and height-diameter functions (Buford 1986, Buford and Burkhart 1987, Knowe and others 1998) because of their utility in expressing stand structure and dynamics in forest growth models. Models developed for eastern cottonwood (*Populus deltoides* L.) plantations have been developed to account for differences in stand basal area and volume (Cao and Durand 1991b) and diameter distributions (Knowe and others 1994).

Research involving large plots of similar genetic composition suggests that the basic growth relationships are similar among loblolly pine seed sources and families. Nance and Wells (1981) and Buford and Burkhart (1987) detected significant differences in site index but not the shape (slope) of height-age profiles. Buford and Burkhart (1987) and Buford (1986) reported similar results for height-diameter functions. Using more flexible models, differences in height growth patterns have been associated with loblolly pine seed sources (Sprinz and others 1989) and half-sib families (Knowe and Foster 1989).

An age adjustment approach (Pienaar and Rheney 1995) has been used to incorporate the effects of silvicultural treatments including fertilization, competition control, and soil tillage (bedding, disking, and subsoiling). This approach involves adding a treatment response function to a yield model for an untreated stand (eq. 1).

$$Y_T = Y_U + \varpi_1 A \exp\left\{\varpi_3 A\right\} \tag{1}$$

where Y_T=yield of treated stand, Y_U=yield of untreated stand, and A=plantation age. The peaking function in equation 1 is sufficiently flexible to represent Types A, B, and C treatment responses. An advantage is that currently available models can be used to represent the yield with standard genetics and only the response function needs to be fit to data from non-standard seedlots. This approach is a departure from the traditional method of site index adjustment but may be useful in modeling genetic effects.

The purpose of this study was to examine the effects of different height-site index curves and age adjustments on basal area and merchantable green weight of open-pollinated loblolly pine families. This represents an extension of an earlier study based on a limited set of data (Knowe 2003). Several goodness-of-fit statistics for the models were compared. Height-site index curves were developed for a commercial check, all improved families combined, and for individual families. Observed height at age five was used to estimate site index and subsequently a predicted height at each measurement age. Predicted heights from the appropriate height-site index curve were substituted into basal area and stand merchantable green weight equations. The stand-level basal area and merchantable weight equations included no age adjustment, an age adjustment for all improved families combined, and family-specific age adjustments. Nine combinations of height-site index curves and age adjustments were examined.

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METHODS

Data

Data from three block-plot experiments involving open-pollinated families of loblolly pine were used to develop and compare models of genetic effects. These experiments included an open-pollinated progeny test established in 1969 near Bogalusa, LA, and two family mixing studies established in 1985 near Bogalusa and Saucier, MS (table 1). The open-pollinated progeny test was planted at 8 by 8 feet spacing, thinned at age 8, and measured at ages 10 and 15 years. The family mixing studies were planted at spacings of 6 by 6 feet and 6 by 3 feet and measured through age 10. All studies included the same unimproved Livingston Parish check lot and six improved open-pollinated families from Livingston and Washington Parishes, LA and southern MS. These families represent good, average, and poor performance relative to the Livingston Parish check lot. After combining the block-plot experiments, 659 observations were available for developing and comparing models of genetic effects.

Explicit Yield System for Loblolly Pine

Following the example of Cao and Durand (1991b), an explicit yield system was used to model genetic effects in open-pollinated families of loblolly pine. The yield system consists of a height-age-site index equation, an equation to predict basal area, and an equation to predict merchantable green weight.

An algebraic difference formulation used by Knowe and Foster (1989) was selected for the height-age-site index equation (equation 2).

$$H_2 = H_1\left\{\left[1-\exp(-\theta_1 A_2)\right]/\left[1-\exp(-\theta_1 A_1)\right]\right\}^{\theta_2} \quad (2)$$

where A_1=current plantation age (years), A_2=projected plantation age (years), H_1=current dominant height (feet), and H_2=projected dominant height (feet). Dominant height is defined as the average height of the tallest 100 trees/acre. Desirable features of this equation are any base age for site index may be selected and each curve has an implied asymptote. Replacing H_2 with site index (SI) and A_2 with base age (25) produces an equation for predicting either dominant height or site index,

$$SI = H\left\{\left[1-\exp(-\theta_1 25)\right]/\left[1-\exp(-\theta_1 A)\right]\right\}^{\theta_2} \quad (3)$$

$$SI = H\left\{\left[1-\exp(-\theta_1 25)\right]/\left[1-\exp(-\theta_1 A)\right]\right\}^{\theta_2} \quad (4)$$

where A=plantation age (years), H=current dominant height (feet), and SI=site index (base age 25). Height and age pairs were arranged in non-overlapping growth series, resulting in 560 observations for developing height-age-site index curves.

Three sets of height-age-site index curves were developed: a Check SI set consisting of one equation for the unimproved check; an Overall SI set consisting of one equation for all improved families combined and one equation for the unimproved check; and a Family SI set consisting of six equations for individual improved families and one equation for the unimproved check. On each plot, observed height at age five was substituted into the appropriate set of equations to estimate site index, which in turn was used to predict heights at each measurement age.

Basal area was computed from the surviving trees on each plot at each measurement age and expressed on a per-acre basis. The following basal area prediction equation was selected to represent the unimproved check lot in this study.

$$SI = H\left\{\left[1-\exp(-\theta_1 25)\right]/\left[1-\exp(-\theta_1 A)\right]\right\}^{\theta_2} \quad (5)$$

where BA=basal area (cubic feet per acre), N=number of surviving trees per acre, A_T=plantation age (years) at time of thinning, N_T=number of trees per acre removed by thinning, N_B=number of trees per acre before thinning, and other terms as previously defined. The model accounts for differences in intensity and timing of thinning. In addition, genetic effects on the height-age-site index curves can be evaluated because dominant height is included in the equation. The basal area prediction equation was fit to data from the unimproved check lot and combined with a variant of the Pienaar and Rheney (1995) age adjustment.

$$BA_{adj} = BA + \varpi_1 A^{\varpi_2}\exp\left\{\varpi_3 A\right\} \quad (6)$$

where BA_{adj}=basal area with an overall or family-specific age adjustment, BA=basal area in equation 5, and other terms as previously defined. As with height-age-site index, three sets of age adjustments were considered in the basal area prediction equation: No adjustment, which consists of the basal area model fit to only the data for the unimproved check; Overall adjustment, which consists of one adjustment for all improved families combined; and Family adjustments, which consist of fitting six different values of ϖ_1 in equation 6 for specific improved families.

Outside-bark merchantable green weight was computed at each measurement age for trees with d.b.h. greater than 4.5 inches on each plot using the Baldwin and Feduccia (1987) variable top diameter equation. Pulpwood was computed to a 3-inch top diameter (outside bark) for trees with d.b.h. between 4.6 and 8.5 inches, inclusive. Green weight of chip-n-saw material was computed to a 6-inch top for trees with d.b.h. between 8.6 and 11.5 inches, inclusive. Sawtimber was computed to an 8-inch top for trees with d.b.h. greater than or equal to 11.6 inches; only the Bogalusa O.P. test had trees that were large enough to be considered sawtimber.

Merchantable green weight of all products on each measurement plot was combined and expressed as tons per acre. The following merchantable green weight prediction equation was selected to represent the unimproved check lot.

$$V = \beta_0 N^{\beta_{11}+\beta_{12}/A} H^{\beta_{21}+\beta_{22}/A}\exp\left\{A^{\beta_3} + \beta_4 \frac{A_T}{A}\frac{N_T}{N_B}\right\} \quad (7)$$

V=merchantable green weight (tons, o.b.), and other terms as previously defined. As with the basal area prediction equation, the merchantable green weight model accounts for differences in intensity and timing of thinning and genetic effects on the height-age-site index curves can be incorporated. The merchantable green weight prediction equation in equation 7 was fit to data from the unimproved

Table 1—Summary of loblolly pine open-pollinated tests used to develop and compare models of genetic effects

Test location	Planting year	Planting spacing (feet)	Trees/ac (measurement plot trees)	Measurement ages and comments
Bogalusa O.P. test (5 replications)	1969	8x8	680 (49 trees)	Ages 1-8, 10, and 15; Thinned at 8
Bogalusa mixing (3 replications)	1985	6x6 and 6x3	1210 (40 trees)	Ages 2, 4, 5, 7, and 10
Harrison Exp. Forest mixing (2-3 replications)	1985	6x6 and 6x3	2420 (40 trees)	Ages 2, 4, 5, 7, and 10

check lot and combined with a variant of the Pienaar and Rheney (1995) age adjustment.

$$V_{adj} = V + \omega_1 A^{\omega_2} \exp\{\omega_3 A\} \qquad (8)$$

where V_{adj}=merchantable green weight with an overall or family-specific age adjustment, V=merchantable green weight in equation 7, and other terms as previously defined. As with height-age-site index, three sets of age adjustments were considered in the merchantable green weight prediction equation: No adjustment, which consists of the merchantable green weight model fit to only the data for the unimproved check; Overall adjustment, which consists of one adjustment for all improved families combined; and Family adjustments, which consist of fitting six different values of ω_1 in equation 6 for specific improved families.

Comparisons

In all, nine possible combinations of three height-age-site index and three age adjustments were evaluated (table 2) and goodness-of-fit statistics were compared. Bias (mean predicted/mean observed), fit index, average deviation, absolute deviation, and error mean square (MSE) of the basal area and merchantable green weight prediction equations were compared for each combination of height-age-site index curve and age adjustment. For bias and fit index, values closer to 1.0 were considered to be best. For average deviation, absolute deviation, and MSE, smaller values were considered better than larger values.

RESULTS AND DISCUSSION

Goodness-of-fit statistics for the basal area prediction equation (equation 6) with height-age-site index and age adjustments to account for genetic effects are compared in table 3.With few exceptions; the differences in fit statistics among methods are small. This suggests that genetic effects are either unimportant or that none of the modeling approaches were particularly effective in predicting differences in yield for open-pollinated families of loblolly pine. Using the height-age-site index curve for the unimproved check lot in combination with the overall age adjustment resulted in the least bias and smallest mean deviation in predicted basal area. The highest fit index, smallest absolute deviation, and smallest MSE was obtained by using the height-age-site index curve for overall improved families in combination with family-specific age adjustments. Using the height-age-site index curve for the unimproved check lot in combination with the family-specific age adjustments resulted in fit statistics that were consistently among the best for predicted basal area. In contrast, using the family-specific height-age-site index curves in combination with no age adjustment resulted in fit statistics that were consistently among the worst. This result is cause for some concern because this approach has been frequently used to account for genetic effects in yield models for loblolly pine (Buford and Burkhart 1987, Knowe and Foster 1989, Nance and Wells 1981, Sprinz and others 1987).

Goodness-of-fit statistics for the merchantable green weight prediction equation (equation 6) with height-age-site index and age adjustments to account for genetic effects are compared in table 4. As with basal area, the differences in fit statistics among methods are small. Using the height-age-site index curve for the unimproved check lot in combination with the overall age adjustment resulted in the least bias and smallest mean deviation in predicted merchantable green weight. The highest fit index, smallest absolute deviation, and smallest MSE was obtained by using the family-specific height-age-site index curves in combination with family-specific age adjustments. Using the height-age-site index curve for overall improved families in combination with the family-specific age adjustments resulted in fit statistics that were consistently among the best for predicted merchantable green weight. However, using the height-age-site index curve for overall improved families in combination with no age adjustment resulted in fit statistics that were consistently among the worst. As with predicted basal area, using the family-specific height-age-site index curves in combination with no age adjustment for merchantable green weight resulted in fit statistics that were consistently among the worst.

Table 2—Nine possible combinations of height-age-site index curves and age adjustments that were considered for incorporating genetic effects into basal area and merchantable green weight prediction equations for open-pollinated families of loblolly pine

	Height-Age-Site Index Curve		
Age Adjustment	Check	Overall	Family
No Adjustment	Check SI No Adj	Overall SI No Adj	Family SI No Adj
Overall Adjustment	Check SI Overall Adj	Overall SI Overall Adj	Family SI Overall Adj
Family Adjustment	Check SI Family Adj	Overall SI Family Adj	Family SI Family Adj

Table 3—Goodness-of-fit statistics for basal area equations using various combinations of site index curves and age adjustments to account for genetic effects represented by open pollinated families of loblolly pine. Statistics include bias, fit index, mean deviation (Dev), mean absolute deviation (Dev), and mean squared error (MSE)

Height-site index curve	Age adjustment	Bias	Fit index	Dev	Dev	MSE
Check	No adjustment	0.9883	0.8858	0.5886	11.0734	228.0427
	Overall adjustment	0.9958	0.8875	0.2099	11.0251	224.7512
	Family adjustment	0.9949	0.8901	0.2565	10.8397	219.4458
Overall	No adjustment	0.9874	0.8865	0.6365	11.0506	226.7683
	Overall adjustment	0.9927	0.8875	0.3652	11.0252	224.7740
	Family adjustment	0.9928	0.8903	0.3645	10.8351	219.1271
Family	No adjustment	0.9876	0.8852	0.6218	11.1131	229.3619
	Overall adjustment	0.9930	0.8861	0.3548	11.0877	227.4295
	Family adjustment	0.9930	0.8899	0.3539	10.8514	219.9447

Table 4—Goodness-of-fit statistics for merchantable green weight equations using various combinations of site index curves and age adjustments to account for genetic effects represented by open pollinated families of loblolly pine. Statistics include bias, fit index, mean deviation (Dev), mean absolute deviation (Dev), and mean squared error (MSE)

Height-site index curve	Age adjustment	Bias	Fit index	Dev	Dev	MSE
Check	No adjustment	0.9699	0.9118	0.4121	4.1457	57.0041
	Overall adjustment	1.0029	0.9137	-0.0396	4.1721	55.7926
	Family adjustment	0.9867	0.9178	0.1822	4.0019	53.0997
Overall	No adjustment	0.9687	0.9108	0.4285	4.1522	57.6335
	Overall adjustment	0.9895	0.9143	0.1436	4.0847	55.3786
	Family adjustment	0.9900	0.9182	0.1368	3.9936	52.8857
Family	No adjustment	0.9691	0.9116	0.4228	4.1423	57.1326
	Overall adjustment	0.9897	0.9150	0.1407	4.0674	54.9202
	Family adjustment	0.9900	0.9182	0.1362	3.9912	52.8618

CONCLUSIONS

For this level of genetic improvement (open-pollinated half-sib families), age adjustments were more effective than using height-age-site index curves to account for differences in yield among families. Fitting age adjustments for individual improved families was slightly better than fitting an overall adjustment for all improved families, and both age adjustments were better than no adjustment. Compared to the height-age curve fit to the unimproved check lot, using height-age-site index curves fit to all improved families combined or to individual improved families resulted in only slight improvements in many of the measures of fit. All three sets of height-age curves resulted in similar fit statistics for both basal area and merchantable green weight. Furthermore, the family specific height-age-site index curves resulted in fit statistics that were consistently among the worst.

Based on these results for open-pollinated families of loblolly pine, a height-age-site index curve for overall improved families should be combined with either overall or family-specific-age adjustments. Refinements in the prediction equations, specifically in the expression for thinning, may improve the fit statistics. The open-pollinated families used in this study represent a wide spectrum of performance, with yields ranging from lower to higher than the unimproved check lot. More detailed examination of these models among individual families is planned.

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THINNING GUIDELINES FROM CROWN AREA RELATIONSHIPS FOR YOUNG HARDWOOD PLANTATIONS

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Abstract—Crown closure in hardwood plantations signals the first opportunity to apply density control treatments such as thinning or release. The proper timing of these treatments is a function of stocking levels and is generally scheduled within several years after initial crown closure. Predicting crown closure for a plantation provides practitioners with the ability to plan intermediate treatments and is based upon crown development in a stand. Stem diameter and crown surface area relationships coupled with plantation spacing and age can be used to estimate crown closure. This study provides crown area relationships for 7- to 10-year-old free-to-grow *Quercus rubra*, *Q. alba*, *Liriodendron tulipifera*, and *Fraxinus americana* trees that were located in five plantations established over a wide range of site conditions from abandoned farm land to reclaimed surface mine sites in Kentucky. Stem ground line diameter ranged 0.5 to 6 inches and regressions of crown and stem diameters of free-to-grow trees indicated acceptable fit statistics with the majority of the species/site R^2 values $\geq$ 0.80.

INTRODUCTION

The scheduling of initial density control treatments in hardwood plantations can vary widely simply due to the range of planting densities common to hardwood plantings. Density control treatments, typically release or thinning, can be scheduled in naturally regenerating hardwood stands upon canopy closure and the timing of the treatment is relatively predictable based on forest type and site productivity. However, the wide range of planting densities associated with hardwoods, along with differences in growth and development associated with site variables, makes the scheduling of the initial release or thinning less consistent than is normally associated with naturally regenerating stands (Sharma and others 2003a). Regardless, tree to tree competition and the reduction in growth associated with competition will determine the biologic basis for the initiation of density control treatments (Curtis 1970). Generally, crown development and crown closure in an individual stand is an indicator of intra-stand tree competition and crown diameter/d.b.h. relationships have been used to establish guidelines for density control in naturally regenerating stands (e.g., Gingrich 1967). Historically d.b.h./crown relationships were determined for open grown trees and used to develop maximum crown areas, crown competition factors (Krajicek and others 1961), and tree area ratios (Chisman and Schumacher 1940) that were used to assess stand stocking providing recommendations for density control. This early work provided density control guidelines that were generalized by forest type. However, each species has unique crown architecture and crown diameter/d.b.h. relationships (e.g., Lamson 1987). Therefore species specific canopy closure models should be developed for monoculture stands or plantations to improve canopy closure predictions leading to density control prescriptions.

For plantations, the initial planting density, species, site, and environmental factors determine the time required for crown closure. Planting density is especially important because it is a known factor that can be controlled (Sharma and others 2003b). On a given site planting density, adjusted for mortality, can be used in conjunction with species specific crown/stem diameter relationships to predict canopy closure and the first opportunity for silvicultural stand density control.

The objective of this study was to determine crown/stem diameter relationships for young open grown trees of economically important hardwood species for the purpose of developing crown closure estimates for artificially regenerated plantings. Ultimately, this information can be used to predict the timing of density control prescriptions for both monoculture and mixed species plantations.

METHODS

Study Area

Sample trees were selected from hardwood plantations established in two physiographic regions of KY. One set of data was collected from two mixed species plantations established on abandoned agricultural land in Hardin and Grayson Counties in southcentral KY in the Pennyrile physiographic region. The second set of data was collected from three hardwood plantings established on surface mined lands in the eastern coal field (Perry and Knott Counties) lying in the Cumberland Plateau physiographic region of eastern KY. The surface mine site was constructed using loose spoil technology providing relatively uncompacted (1.4 to 1.8 mg/m^3) pH neutral spoil for planting to replace the relatively thin and clay rich naturally occurring soils common to the region. Initial survival and growth in both regions was similar. The temperate climate is also similar in both regions with precipitation averaging 118 cm (46.5 inches) per year. The average annual temperature is 13 °C with an average frost-free period of 180 days.

Hardwood Seedlings

In both regions mixed species hardwood plantations had been established using 1-0 bare-root seedlings. Ages of the plantations sampled ranged from 7 to 10 years and individual g.l.d. (ground line diameters, 1 inch above mineral soil) ranged 0.5 to 6 inches. Initial spacing of the plantations

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ranged from 6 by 6 feet to 12 by 12 feet, (1 200 and 300 trees per acre, respectively). For the purpose of this study only open growing northern red oak (*Quercus rubra*), white oak (*Q. alba*), yellow-poplar (*Liriodendron tulipifera*), and white ash (*Fraxinus americana*) trees were sampled across the range of g.l.d. available at each planting site. A total of thirty open grown trees of each species were sampled on agricultural lands and 135 trees per species were sampled on surface mine lands. Trees were selected for study if they were free-to-grow as indicated by at least two feet of free growing space on all sides of the crown. Trees having evidence of browse, mowing damage to stem or crown, main-stem forking, or dead or dying branches were not sampled.

Crown/Stem Diameter Measurements

G.l.d. was measured to the nearest 0.25 inch and horizontal crown diameters were measured with the aid of an ultrasound remote and transponder on two perpendicular axes. The outer limits of the crown were delineated by the lateral bud located farthest from the stem. Average horizontal crown diameters were used to determine horizontal crown surface areas and well as regressed against g.l.d. by species by plantation. As expected, simple linear regression was found to adequately describe the g.l.d. and horizontal crown diameter relationship for each species. Analysis of variance (ANOVA) was used to determine goodness-of-fit among regression variables (alpha level was set at 0.05). Significance among species was determined by the differences in least square means of the slope for each plantation and species using SAS software. No significant differences in species regression slopes were found among plantations within a region and plantation data were pooled within a region for further analysis.

Crown/stem diameter relations of northern red oak were combined with growth data and horizontal crown surface area and used to provide an example of how crown/stem diameter relations could be used to project crown closure, and thus the projected first entry period for release and/or thinning, in hardwood plantations.

RESULTS AND DISCUSSION

Coefficients of determination (R^2) ranged from 0.7606 to 0.8871 for crown and stem diameter linear regressions across all species and sites. Only northern red oak showed a significant difference in regression slope between regions at the $p \leq 0.05$ level (table 1). Northern red oak on the surface mined land produced a slope of 2.4334 compared to 1.7423 for agriculture land. This difference indicates the surface mine trees have a larger canopy diameter per increment of stem diameter. For example, a 2-inch red oak stem on the agriculture site has a canopy diameter of approximately 4 feet compared to 4.75 feet on the surface mine site. Regression slopes for other species did not differ significantly between regions.

Regression slopes among species on agricultural lands were statistically similar ($p \leq 0.05$) with the exception of white oak and yellow-poplar (p=0.0177) with white oak exhibiting a wider crown than yellow-poplar. While not statistically significant, there was a trend for northern red oak to exhibit a similar pattern. On surfaced mined lands white oak exhibited a significantly lower slope than the other species. Figures 1 through 4 show the individual tree data points and the average simple linear regression equations for all study trees by species providing generic crown/stem relationships. Coefficients of determination for the generic species equations ranged 0.7716 for white ash to 0.8829 for yellow-poplar. It is reasonable that these generic equations could be used by practitioners for developing average site occupancy and crown closure estimates when site specific data is not available. Figure 5 shows plots of the individual species equations for agricultural plantations and figure 6 shows plots for trees on surfaced mine sites. As previously discussed, the data indicate that crown/stem relationship can be affected by site. However, from a practical standpoint these differences

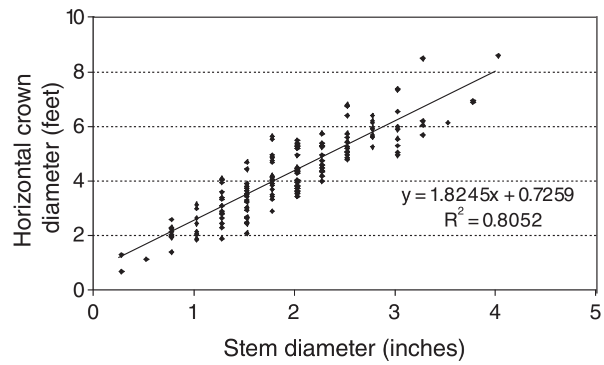

Figure 1—Average crown/stem diameter relationship for white oak (*Q. alba*).

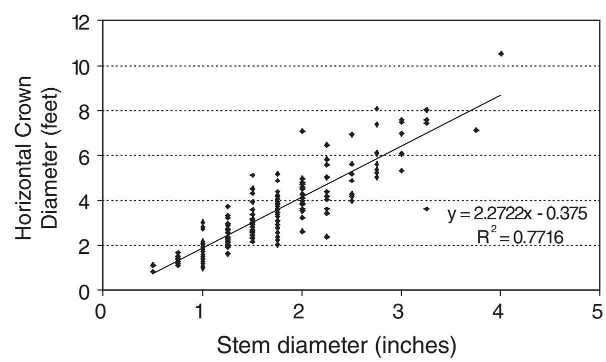

Figure 2—Average crown/stem diameter relationship for white ash (*Fraxinus americana)*.

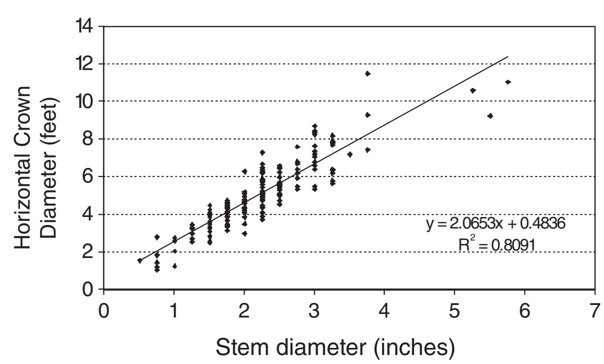

Figure 3—Average crown/stem diameter relationship for northern red oak. (*Q. rubra)*.

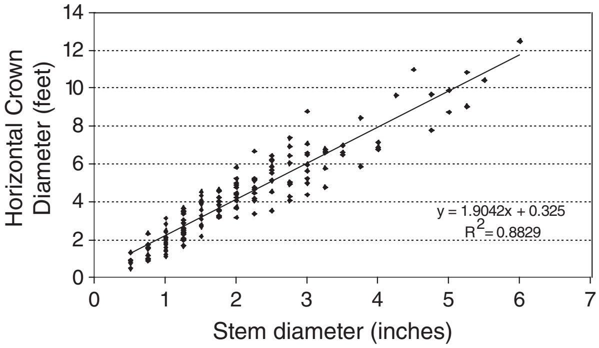

Figure 4—Average crown/stem diameter relationship for yellow-poplar (*Liriodendron tulipifera)*.

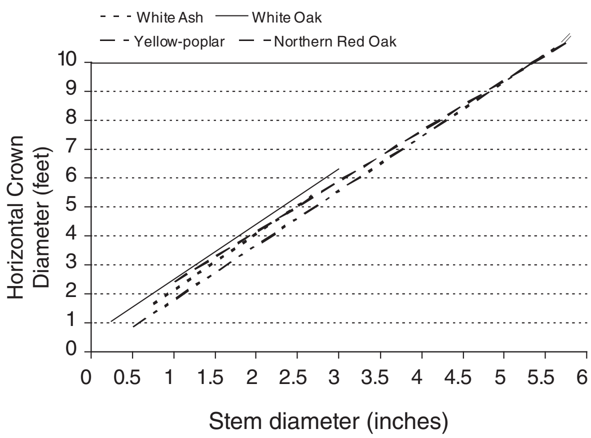

Figure 5—Linear regressions for hardwood plantations on agriculture land.

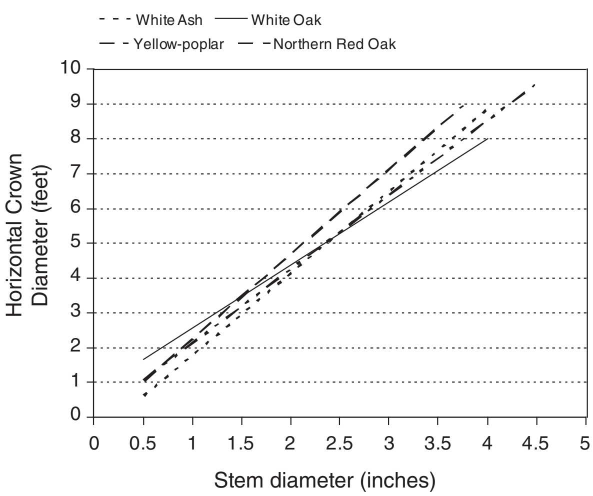

Figure 6—Linear regressions for hardwood plantations on surface mines.

are small and the data can be used to provide reasonable estimates of crown closure over a wide geographical area.

The resulting regressions provide a reasonable means of predicting when crowns will start to touch (crown closure) and when the site is fully occupied by canopy (canopy closure) for varying planting densities. Figure 7 is one example of how this data can be used for predicting site occupancy and

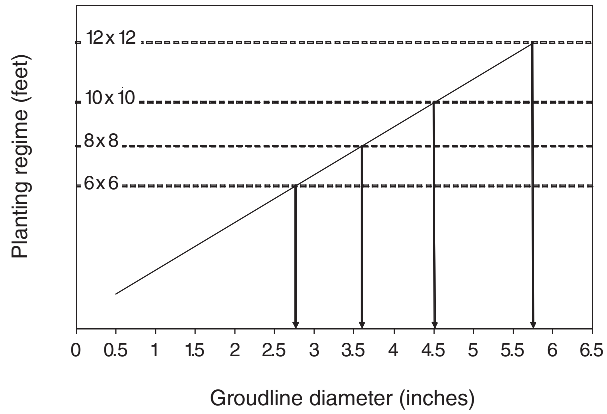

Figure 7—Estimation of ground line stem diameters required for crown closure for northern red oak (*Q. rubra*).

possible thinning regimes at a given planting density. The sloped line is the generic northern red oak regression. The X-axis is the average diameter of trees in the plantation and the Y-axis is the point at which trees at a given spacing would initiate crown closure. The solid horizontal lines indicate the point where crown closure starts for typical spacing's (assuming 100 percent survival). By following the horizontal line of a given spacing to the slope line and following down to the X-axis the practitioner can determine what average ground line diameter is required to achieve crown closure for a given spacing. This assumes 100 percent survival and that the crown/stem diameters for the trees in the planting are similar to ones found in this study. The latter assumption is reasonable given the similarity of relationships among the five dramatically different soils and sites sampled for this study. This method is a quick and easy way to predict future stand level growth parameters for hardwood plantations. Using the equations regenerated in this study, practitioners can determine estimates of site occupancy (ground cover) over time and estimate time required for crown closure of plantings. These estimations will improve their ability to schedule intermediate treatments and improve overall plantation growth and development.

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NATIONAL WORKSHOP ON FOREST PRODUCTIVITY & TECHNOLOGY: COOPERATIVE RESEARCH TO SUPPORT A SUSTAINABLE & COMPETITIVE FUTURE—PROGRESS AND STRATEGY

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Abstract—The Agenda 2020 Program is a partnership among government agencies, the forest products industry, and academia to develop technology capable of enhancing forest productivity, sustaining environmental values, increasing energy efficiency, and improving the economic competitiveness of the United States forest sector. In November 2006, the USDA Forest Service, in partnership with the Agenda 2020 Technology Alliance, the American Forest and Paper Association, the National Council for Air and Stream Improvement, and U.S. Department of Energy, organized a national workshop to document and discuss significant achievements and build support for the Agenda 2020 Sustainable Forest Productivity program and related research. The workshop was organized into sessions on: (1) Forest Management, Soil Productivity, and Information Technology; (2) Biotechnology and Tree Improvement; (3) Physiology, Growth, and Wood Quality; and (4) Ecological Functions of Managed Forests. Since 1999, Forest Service Research & Development and partners have funded 66 projects. A summary of key results and potential future research direction will be presented.

INTRODUCTION

The Agenda 2020 Program is a partnership among government agencies, the forest products industry, and academia to develop technology capable of enhancing forest productivity, sustaining environmental values, increasing energy efficiency, and improving the economic competitiveness of the United States forest sector. In 1994, the forest products industry developed a technology vision and the research pathways required for a sustainable future (American Forest and Paper Association 1999). Six broad research areas were identified, including sustainable forestry, with the goal of promoting research and technology development for the sustainable management of forest resources to ensure future availability and use. Since 1998, U.S. Forest Service R&D (FS R&D), along with U.S. Department of Energy (DOE) and the American Forest and Paper Association (AF&PA), has supported the Sustainable Forest Productivity pathway in Agenda 2020. Initially, the Sustainable Forest Productivity pathway contained four areas of emphasis: biotechnology and tree improvement, soil productivity, physiology of forest productivity, and forest information technology. In 2006, the Agenda 2020 Forest Products Industry Technology Roadmap was developed (Agenda 2020 Technology Alliance 2006). The goal of the Roadmap is to develop and deploy wood production systems for our nation's forests that are ecologically sustainable, socially acceptable and economically viable, thereby enhancing our understanding of our forest ecosystems and the global competitiveness of forest-based manufacturing and biorefinery systems in the United States. Sustainable forest productivity continues to be one of the technology platforms used to meet this goal. Sustainable forest productivity focus areas are biotechnology and tree improvement, improving wood quality delivered to mills, forest management, and optimizing ecological functions of managed forests.

Since 1997, a total of 94 research projects have been funded under the Sustainable Forest Productivity Platform of Agenda 2020 through a competitive process. Twenty-eight projects have been funded by DOE since 1997 and 66 projects have been funded by FS R&D since 1998. Of the 66 projects, 40 have been funded through Forest Service Research Stations in regional programs and 26 have been funded through the FS R&D Washington Office in the national program. The $12 million in FS R&D funding has leveraged an additional $8 million in cooperator contributions.

In November, 2006, the "National Workshop on Forest Productivity and Technology: Cooperative Research to Support a Sustainable and Competitive Future" was held with the objective of presenting key results and discussing future research direction of the Agenda 2020 Sustainable Forestry Program. The workshop was sponsored by the Agenda 2020 Technology Alliance, AF&PA, National Council for Air and Stream Improvement (NCASI), DOE, and FS R&D. This paper summarizes key outcomes presented at the Agenda 2020 Sustainable Forest Productivity Workshop.

FOREST MANAGEMENT, SOIL PRODUCTIVITY, AND INFORMATION TECHNOLOGY

This area focused on research leading to significant improvements in long-term soil productivity and new applications of information technology that will improve forest management systems and enable significant gains in fossil energy efficiency and environmental quality. Deployment of results will be through application of state of the art management practices and technologies to improve forest health and productivity. The following are key results presented.

Long-term Implications of Management Practices on Site Productivity and Controlling Processes

This work focuses on enhancing understanding of the consequences of biomass manipulation, ground-based harvesting, and vegetation control for short and long-term forest productivity in the Pacific Northwest (Ares and others 2007). Removal of organic matter at the time of harvest did not have a detectable influence on soil water content (SWC) during

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the 4th and 5th years after plantation establishment (Devine and others 2006) and there was no significant difference in tree size associated with amount of biomass removed (Roberts and others 2005). The ratio of total carbon above the mineral soil to total carbon within the mineral soil was markedly altered by biomass removal, but proportions of total N stores were reduced only three to six percent owing to the large soil N reservoir on site (Ares and others 2007). Soil compaction in traffic lanes affected soil properties but did not exceed critical levels (Ares and others 2005). These results help refine understanding of how different soils respond to management, provide data to support the design of best management practices (BMPs), and provide critical information for the practice of precision forestry at multiple scales.

Options for Increasing the Sustainable Harvest Level and Value of Spruce-Fir in Maine

The objective of this study is to improve the management, health and productivity of, as well as economic returns from, northeastern spruce-fir forests. Initial results show that precommercial thinning in spruce-fir forests in Maine increases total stand volume over unthinned stands. In addition, these treatments can double maximum net present value (NPV) of the stand and cause the maximum (NPV) to be reached 10 to 15 years sooner than in unthinned stands (Keefe and Wagner 2004, Wagner 2006,Wagner and Keefe 2005).

Science to Develop Silvicultural Practices to Enhance Carbon Sequestration

Intensive silviculture of loblolly pine (*Pinus taeda* L.) provides potentially large increases in biomass production and net ecosystem productivity (NEP). Increasing site resources enhanced the rate of carbon sequestration (Maier and others 2004) and relationships between temperature, soil type, region, and stand development and soil CO_2 efflux were variable (Gough and others 2005). Work is continuing to quantify the effects of added organic matter on soil carbon dynamics, soil nutrient supply, and pine productivity; as well as the response of contrasting genotypes to management practices and resource manipulations.

Extension of Light Detection and Ranging (LIDAR) as a Tactical Management Tool

This research and development effort is focused on creating useful, cost-effective applications of LIDAR remote sensing for precision forest management. Current efforts are focused on relating LIDAR observations to plot validation data. Results show that LIDAR height is a good predictor of basal area and LIDAR-based canopy cover is a good predictor of tree density (Evans and Hudak 2007, Falkowski and others 2006, Hudak and others 2006).

Genetic Markers for Pathogenic *Armillaria ostoyae* and Web Tool for Risk Estimation

Genetic markers were successfully developed to distinguish pathogenic *Armillaria ostoyae* from other beneficial or non-pathogenic *Armillaria* species (Hanna and others, In press). Genetic relationships among *Armillaria* species and genets have been evaluated (Kim and others 2006). Preliminary methods and tools to predict Armillaria disease risk based on environmental factors and to predict potential invasive risks posed by *Armillaria* spp. are being developed (McDonald and others [In press]).

BIOTECHNOLOGY AND TREE IMPROVEMENT

This area focuses on development and deployment of superior trees that will result in significant gains in forest productivity, fossil energy efficiency, and environmental quality. The goal is to develop and deploy genetically superior planting stock with demonstrated potential to reduce wood production costs and improve wood quality for a variety of uses.

Gene discovery for adaptive traits in Douglas-fir (*Pseudotsuga menziesii*)

Research on cold adaptation genes in Douglas-fir has led to the identification of 400 Douglas-fir unigenes as cold adaptation candidate genes. Eighty-eight amplicons produced useable sequences and these are being used to develop an automated pipeline for base calling and sequence alignment. Work continues to verify in Douglas-fir associations between candidate genes by wood property phenotype associations that were initially discovered in loblolly pine (Howe 2006, Krutovsky and Neale 2005, Krotovsky and others 2004).

Engineering Flowering Control in Poplar and Other Species

Genetically engineered flowering control is important as a means of confining transgenes, maintaining rapid growth, and preventing potential genetic pollution – all of which are important for developing trees as a biofuel feedstock. So far, poplar floral promoters with floral-specific expression that work in a variety of plants have been identified (Brunner and others 2000, Meilan and others 2001, Meilan and others 2004, Rottmann and others 2000, Skinner and others 2003, Wei and others 2005). Ongoing work is focused on modifying a variety of genes to build in redundancy and on determining the stability of transgene expression.

Engineering Cellulose Biosynthesis in Trees

This research is aimed at developing ways to genetically augment the syringyl-to-guaiacyl lignin ratio in low-lignin transgenic aspen in order to produce trees with reduced lignin content, more reactive lignin structures, and increased cellulose content. Results show that sinapyl alcohol dehydrogenase (SAD) is required for the biosynthesis of syringyl lignin in angiosperms (Li and others 2001). A multigene cotransfer system has been developed that should be broadly useful for plant genetic engineering and functional genomics (Li and others 2003). Results confirm that the coniferaldehyde 5-hydroxylase (CAld5H) gene is key to syringyl lignin biosynthesis, and that genetic manipulation of both lignin content and lignin composition in pulpwood species may be achieved via gene stacking (Tsai and others 2004a, Tsai and others 2004b). Future issues to be addressed include pilot-scale pulping analysis, and field and regulatory evaluations to complete the technology assessments.

Developing Genomic Knowledge Base for Facilitating Tree Breeding

A large number of high quality genetic markers are needed for marker assisted selection and breeding in loblolly pine. The effort to develop an expressed sequence tags (EST) database for loblolly pine has facilitated the development of 145 new short simple repeat (SSR) or microsatellite markers. On the order of 1 000 single nucleotide polymorphism (SNP) markers can be developed with existing EST database (Chagne and others 2004). The challenge is estimating the value of specific alleles in populations and optimally using the information in selection and breeding programs.

PHYSIOLOGY, GROWTH, AND WOOD QUALITY

Research in this area focuses on wood formation and wood quality, ecophysiology of planted forests, and nutrient use efficiency. Developments leading to significant gains in forest productivity and environmental performance result from more rapid advances in forest biotechnology and improvements in silvicultural practices.

Candidate Gene List Generation and Validation for Resource Allocation in Populus

This research has focused on determining the mechanisms that regulate the biochemical and genetic physiology of poplar trees with regard to nitrogen utilization. This will allow cost-effective strategies for applying nitrogen to be developed and deployed by matching the timing and quantity of nitrogen application to the specific requirements of the trees. Nitrogen-responsive cDNAs have been cloned and sequenced (Lawrence and others 2001). The gene expression data suggest that N availability modulates the partitioning of C and N resources into metabolic fates that have the potential to alter both wood quality and quantity (Cooke and others 2003). Nitrogen availability modulated parameters that affect carbon gain include light-saturated net photosynthesis and leaf area. Genes encoding vegetative storage proteins and starch biosynthetic enzymes exhibited contrasting patterns of expression under differential N availability (Cooke and others 2005).

Physiological Limits of Productivity

This study was designed to create optimal growing conditions for loblolly pine through intensive manipulation of water and nutrient regimes. Irrigation plus fertilization reduced annual soil carbon loss and greatly increased belowground carbon sequestration relative to a control, but soil CO_2 efflux (S_{CO2}) was not correlated to fine root mass. Annual S_{CO2} declined linearly with increasing belowground carbon content in root biomass at age six (Samuelson and others 2004b). Through age six, results show that changes in leaf-level physiology appeared important only at the seedling stage. There is little change in allocation between above- versus belowground tissues; there appears to be no threshold basal area observed after which stem production declines and increased growth appears to be a result of LAI maintenance and low tree mortality (Samuelson 1998, Samuelson and others 2004a, Samuelson and others 2001, Samuelson and Stokes 2006). Growth rate observations indicate that very intensive management can push loblolly pine closer to its genetic growth potential.

Preliminary Methods for Predicting Latewood-Earlywood Ratios from Foliar Stable Carbon Isotope Signatures

This research aims to improve wood quality in managed southern pine forests through better understanding of the relationships among tree xylem cell structure, tree water relations, and wood quality characteristics such as specific gravity and latewood:earlywood (LW:EW) ratio. It is hypothesized that genetic variation in LW:EW alters xylem hydraulic properties, which causes variation in physiological characteristics related to water relations, such as foliar stable carbon isotope discrimination (Δ13C). Understanding and quantifying these relationships should lead to increased understanding of adaptive structure-function relationships, and the development of practical tools for screening breeding populations for wood quality characteristics. Hypotheses regarding the relationships between water stress and latewood formation will be tested and corroboration of previously-documented correlations between foliar Δ13C and growth rate will be attempted. Initial results indicate that xylem hydraulic conductance, late wood percent, and specific gravity are generally higher in irrigated plots than in unirrigated plots across the genotypes tested (Personal Communication. Dr. Timothy A. Martin. 2007. Associate Professor, University of Florida, 359 Newins-Ziegler Hall, P.O. Box 110410, University of Florida, Gainesville, FL).

Effects of Growth Rate and Genetics on Wood Quality of Coastal Douglas-fir

Swiss needle cast disease resulting from *Phaeocryptopus gaeumannii* increases wood strength and stiffness in coastal Douglas-fir more than changes in growth rate alone (Johnson and others 2003). Phenotypic correlations of ring width and wood properties are statistically significant, probably of little practical importance, and mostly due to genetics (Johnson and others 2005). Genetic correlations indicate that wood properties are important to consider in breeding programs and can be incorporated because it is relatively easy to monitor the modulus of elasticity and wood density (Grotta and others 2005, Johnson and Gartner 2006).

Quantifying and Predicting Wood Quality of Intensively Managed Loblolly Pine and Slash Pine (*Pinus elliottii*)

Competition control does not appear to affect age-specific wood density or length of juvenility. Woody and herbaceous competition control combined did not significantly reduce annual ring specific gravity (SG) of earlywood or latewood, and did not significantly affect the proportion of latewood in the annual rings (Clark and others 2006b). Vegetation control treatments had no consistent effect on the length of juvenility (Clark and others 2006b). Precisely estimating the age of transition between juvenile and mature wood is difficult because transition in loblolly pine is gradual rather than abrupt (Clark and others 2006a). A model describing changes of earlywood and latewood microfibril angle (MFA) within the tree has been developed (Jordon and others 2005). Annual heavy fertilization alone or in combination with vegetation control significantly reduced toughness as well as strength and stiffness of juvenile wood (Clark and others 2004).

ECOLOGICAL FUNCTIONS OF MANAGED FORESTS

Research in this area focuses on methods and tools to understand, quantify, optimize, and communicate current and potential contributions of managed forests to ecosystem functions, including watershed management, carbon sequestration, wildlife habitat, and renewable feedstock supply for bioenergy and bio-based products and chemicals.

Estimating Cumulative Effects on Multi-ownership Landscapes

Research in this area has provided a tool for evaluating cumulative effects of forest management activities on multiple ownership landscapes (Gustafson and others 2007). Results can be used to simulate how the actions of each owner influence the overall pattern of vegetation and age arrangement on the landscape, and to help evaluate cooperative strategies to manage landscape patterns (Gustafson and Loehle 2006, Gustafson and others 2007).

The Role of Species and Climate in Carbon Cycling and Sequestration in Pine and Hardwood Forests

Carbon allocation and storage in coarse roots varies with stand age and species. Ecosystem carbon storage varies with age and species. Species did not alter soil carbon quality, but may alter the quantity of soil carbon. Across a geographical gradient in temperature in the United States, increasing mean annual temperature appears to modestly alter soil quality and quantity, and increase total belowground carbon allocation (Giardina and others 2005).

CONCLUSIONS

Our Nation's forests are a sustainable, strategic asset in achieving and enhancing United States energy security, economic opportunity, environmental quality, and global competitiveness. Substantial progress is being made in developing management systems that are sustainable, highly productive and energy efficient. However, we must consider the range and quantity of goods, services, and values demanded from forests in the coming decades. In significant measure, we will expect these lands to produce water, wood and non-wood products, recreational opportunities, varying habitats, climate change mitigation, and energy needed by our growing population and its economies. Continuing growth in global populations, economic development and prosperity, and demand for forest products and energy underscores the critical need to produce more wood on fewer acres.

Through collaboration and commitment, the Agenda 2020 Sustainable Forest Productivity Program has supported excellent forestry research projects that have produced new knowledge with important practical implications and applications. The program has played a key role in revitalizing public/private partnerships in the forestry research and development community in the United States. The strengths of the Agenda 2020 Sustainable Forest Productivity Program are: (a) the partnerships created between the research community and users of scientific information; (b) its regional and national components; (c) its unique, strategic focus on critical research and development priorities related to wood production systems and their linkages to economic development, environmental performance, and energy security; (d) the rigorous, competitive process is used to select projects; and (e) its inclusions of critical research and technology transfer. Current focus areas for Sustainable Forest Productivity in Agenda 2020 are biotechnology and tree improvement, improving wood quality delivered to mills, forest management, and optimizing environmental services from managed forests (Agenda 2020 Technology Alliance 2006). Future partnerships can build upon the strengths of our current Agenda 2020 Sustainable Forest Productivity Program.

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COMPARING METHODS TO ESTIMATE REINEKE'S MAXIMUM SIZE-DENSITY RELATIONSHIP SPECIES BOUNDARY LINE SLOPE

Curtis L. VanderSchaaf and Harold E. Burkhart[1]

Abstract—Maximum size-density relationships (MSDR) provide natural resource managers useful information about the relationship between tree density and average tree size. Obtaining a valid estimate of how maximum tree density changes as average tree size changes is necessary to accurately describe these relationships. This paper examines three methods to estimate the slope of the MSDR species boundary line across a range of site qualities: ordinary least squares, first-difference model, and the linear mixed effects model.

INTRODUCTION

According to the theoretical reasoning behind stand density index (SDI), all stands should eventually approach and track along the same Maximum Size-Density Relationship (MSDR) boundary for a particular species/region combination (Reineke 1933, Drew and Flewelling 1977, Williams 1996, Harms and others 2000). The MSDR is commonly expressed in terms of SDI as seen in equation (1):

$$SDI = TPA^*(QMD/10)^b \qquad (1)$$

where:
TPA = trees per acre
QMD = quadratic mean diameter (inches)
b = MSDR boundary coefficient

Generally, for the model form used in equation (1), b is assumed to be near 1.6. Usually, b is obtained by regressing LnTPA against LnQMD which gives a negative b. Williams (1996) shows how equation (1) is derived from the LnTPA-LnQMD regression and how b becomes positive when used in equation (1). Although this study pertains to estimating the b of Reineke's MSDR, this analysis also applies to the well-known Self-thinning rule (Westoby 1984, Weller 1987) which uses average volume or average biomass rather than average diameter.

Reineke (1933) conceptualized the MSDR boundary as a linear asymptote on the log-log scale that all stands would eventually approach and track along for a particular species/region combination. Since that time ecologists and foresters have proposed modifications to the theory behind the self thinning concept. For the remainder of this paper, the terminology of Weller (1990) will be used:

1. Individual stand MSDR boundaries will be referred to as MSDR dynamic thinning line boundaries. We assume a plot to be representative of a stand.
2. The MSDR species boundary line I shall be defined as a static upper limit of maximum tree density-average tree size relationships (or conversely maximum average tree size-tree density relationships) that applies to all stands of a certain species within a particular geographical area.

For the MSDR species boundary line I, "static" refers to the fact that mid-rotation and regeneration management techniques, site quality, genetics, etc., have no impact on this boundary line as opposed to MSDR dynamic thinning lines which can be affected by genetic stock and silvicultural treatments (VanderSchaaf and Burkhart 2007, Weller 1990). The MSDR species boundary line I is a line of constant slope connecting maximum tree densities across a range of average tree sizes regardless of site quality, planting density, genetics, thinnings, etc. Maximum tree densities across the range of average tree sizes can be a conglomeration from many stands and the maximum tree densities are not necessarily obtained from an individual stand (VanderSchaaf and Burkhart 2007). Conversely, the axes can be rotated such that the MSDR species boundary line I is a line of constant slope that connects the maximum average tree size for a given TPA regardless of site quality, planting density, genetics, thinnings, etc.

VanderSchaaf and Burkhart (2007) proposed a second definition of the MSDR species boundary line—what they called the MSDR species boundary line II. The slope of the MSDR species boundary line II is considered to be the population average of all MSDR dynamic thinning line slopes for a particular species. Due to the impacts of planting density on MSDR dynamic thinning line boundary levels, the ordinary least squares (OLS) estimate of b was found to be sensitive to the range of planting densities included in the model fitting dataset. Since all observations are considered independent, OLS accounted for differences in dynamic thinning line boundary levels by adjusting both the species boundary line intercept and slope terms.

Despite the belief that MSDR dynamic thinning line boundary levels are independent of site quality (Reineke 1933), studies have found site quality can impact boundary levels for conifer species (Hynynen 1993, Pittman and Turnblom 2003) including loblolly pine (*Pinus taeda* L., Strub and Bredenkamp 1985, Harrison and Daniels 1988). These studies imply the greatest TPA that can occur for a particular QMD is larger on higher quality sites, or that not all MSDR dynamic thinning line boundaries occur along the MSDR

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species boundary line. If differences in the boundary level due to site quality are not accounted for when estimating the b of MSDR species boundary lines, the estimated b may not be reflective of how individual stands self-thin during the MSDR dynamic thinning line stage of stand development (VanderSchaaf and Burkhart 2007). See figure 1.

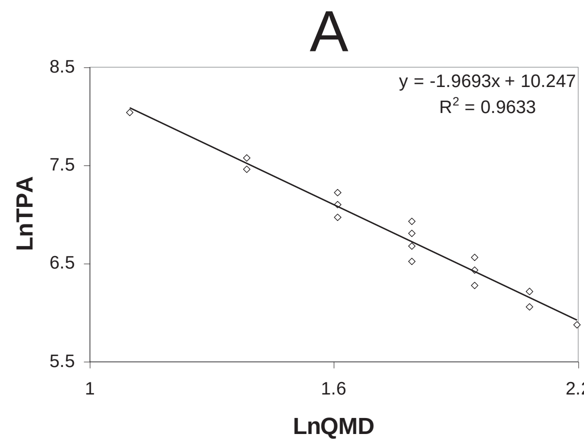
Often, the MSDR species boundary line is used as a limit for stand density in models (Oliver and Powers 1978, Puettmann and others 1993, Smith and Hann 1984). Monserud and others (2005) describe the utility of limiting stand density using self-thinning constraints. When using self-thinning constraints, stand development is predicted using equations independent of the self-thinning constraint until the stand reaches the upper boundary. Stand tree density or average tree size is then constrained such that the stand trajectory tracks along this upper boundary either for a limited amount of time before diverging from the boundary or the stand tracks along this upper boundary into infinity. There are several statistical methods to estimate b that includes OLS, first-difference models, and mixed models. When growth and yield models are constrained by MSDR species boundary lines using an estimated b, an improper estimated value of b can produce serious errors in estimation of stand density development, stand yield, and ultimately economic decisions.

The objectives of this study were to: (1) ascertain whether different statistical methods used to estimate the MSDR species boundary line b result in varying values, and (2) determine whether certain statistical methods produce more stable estimates of the MSDR species boundary line II b as the range of site quality in the fitting dataset varies.

METHODS

Data

Tree and stand measurements were obtained from a long-term loblolly pine plantation thinning study maintained by the Loblolly Pine Growth and Yield Research Cooperative at Virginia Polytechnic Institute and State University. Permanent research plots were established from 1980 to 1982 on 186 sites located throughout the Southeastern United States (Burkhart and others 1985). At each study site location, three plots were established; one was left unthinned and the two other plots were thinned. For this current analysis, only the unthinned plots were used to eliminate the potential affects of mid-rotation thinning on MSDRs. Plots were remeasured every three years and the number of remeasurements differed across sites due to factors such as clearcutting, insect or disease damage, etc. For sites where planting density is known, it ranged from 570 to 1223 seedlings per acre. Site quality was measured as site index at base age 25. To estimate site index for an individual plot, the average height of the tallest half of the surviving trees for the measurement age closest to age 25 was placed into a site index equation developed by Burkhart and others (1987). Site index ranged from 41 to 76 feet and averaged 56.



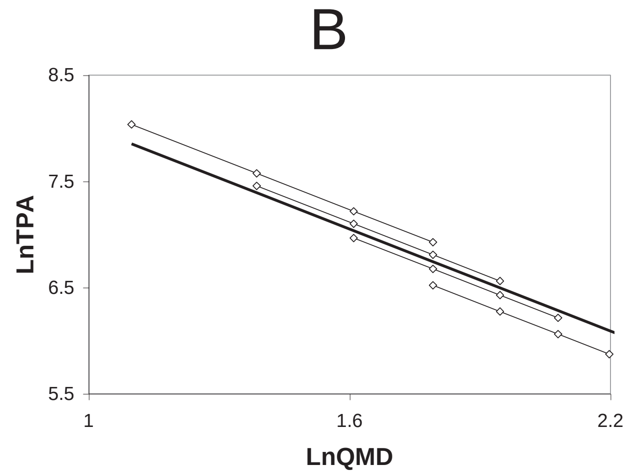


Figure 1—LnTPA over LnQMD for four theoretical stands where each stand has a MSDR dynamic thinning line slope of -1.6. Lighter lines connect observations from the same stand in Figure 1-B. One stand has a Reineke SDI of 450, a second stand has a Reineke SDI of 400, a third stand has a Reineke SDI of 350, and a fourth stand has a Reineke SDI of 300, differences in Reineke's maximum SDI are attributed to differences in site quality. The LnQMD of observations occurring along MSDR dynamic thinning lines also differ by site quality. In Figure 1-A, all observations are assumed independent of one another. When using OLS to estimate the MSDR species boundary line slope, an estimate of -1.9693 is obtained because OLS ignores differences in boundary levels, or correlation among observations from an individual MSDR dynamic thinning line. When using a mixed effects model, a slope of -1.6 is estimated since the technique accounts for differences in MSDR dynamic thinning line boundary levels (or accounts for correlation among observations from the same MSDR dynamic thinning line) when estimating the MSDR species boundary line slope.

Stages of Self-Thinning in Individual Stands

Within the overall self-thinning stage of stand development, or when density-dependent mortality is occurring, there is generally considered to be three stages of stand development (VanderSchaaf and Burkhart 2007):

1. The self-thinning stage of stand development is initially composed of a curved approach to the MSDR dynamic thinning line. During this initial component of self-thinning, mortality is less than the mortality at maximum competition and thus the trajectory has a concave shape (del Rio and others 2001).
2. With increases in individual tree size and the death of other trees, eventually the growth trajectory becomes linear where an increase in QMD is assumed to be an exact function of the maximum value of Reineke's SDI, the change in TPA, and the MSDR dynamic thinning line b. This stage is known as the MSDR dynamic thinning line stage of stand development (Weller 1990), or when a stand is fully-stocked (del Rio and others 2001).
3. Eventually, as trees die, the residual trees cannot continue to fully occupy canopy gaps and the trajectory diverges from the MSDR dynamic thinning line (Bredenkamp and Burkhart 1990, Cao and others 2000, Zeide 1995).

Over the entire range of self-thinning the relationship between LnQMD and LnTPA is curvilinear; however, this analysis deals only with the linear stage (or portion) of the trajectory (Cao and others 2000, del Rio and others 2001, Monserud and others 2005, VanderSchaaf 2006, Yang and Titus 2002, Zeide 1985).

Determining What Observations Occur Along MSDR Dynamic Thinning Line Boundaries

Graphs of LnQMD over LnTPA were constructed for each unthinned study plot to determine when stand trajectories had reached a MSDR dynamic thinning line boundary. In order to be consistent with the recommendations of Weller (1987, 1991), visual inspection of all plots was conducted to ensure that only those observations occurring along a MSDR dynamic thinning line boundary were included when estimating the MSDR species boundary line b coefficient (fig. 2A).

Slopes of individual MSDR dynamic thinning line boundaries were greatly affected by measurement ages that were diverging from MSDR dynamic thinning line boundaries—stage 3 of self-thinning. Therefore, all points diverging from individual MSDR dynamic thinning line boundaries were eliminated when determining the MSDR species boundary line b. If a plot had two consecutive points along the MSDR dynamic thinning line—a growth trajectory moving in a straight line (MSDR dynamic thinning line) to the left—the plot was included in the analysis. Data were obtained from 121 of the 186 sites. Measurement ages at which observations occurred along a MSDR dynamic thinning line

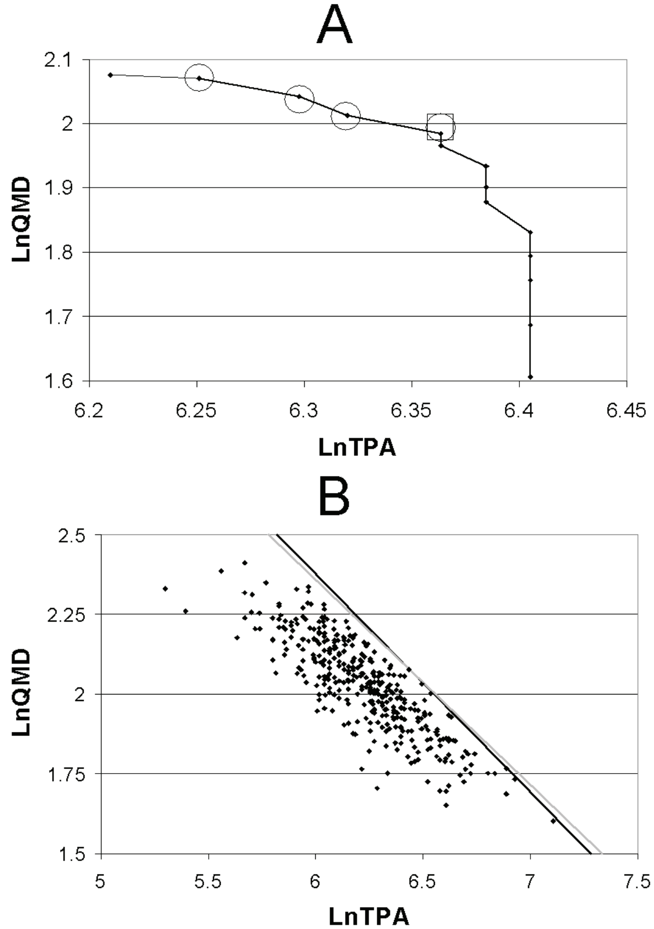


Figure 2—A. Loblolly pine growth trajectory for a planting density of 605 seedlings per acre. Vertical movements of the trajectory indicate the plantation is not self-thinning, while movements to the left and up indicates the plantation is self-thinning. A constant "linear" movement to the left and up indicates the trajectory has reached the MSDR dynamic thinning line boundary for that individual plantation. Therefore, the measurement ages with circles around them were used to estimate the b for the OLS and linear mixed effects analyses. For the first-difference model and the Mean slope calculation method, the observation with a square was omitted when determining b values between two successive measurement ages. The last measurement age was not included in the analysis because it is diverging from the MSDR dynamic thinning line boundary.
B. Plot of all individual LnQMD-LnTPA observations (n = 365) occurring along MSDR dynamic thinning line boundaries. The figure also contains OLS (black line) and linear mixed effects (gray line) estimated MSDR species boundary lines that have b's of -1.4593 and -1.5537; respectively. Boundary lines were positioned above all observations.

boundary ranged from 19 to 42 years. For the observations occurring along MSDR dynamic thinning lines, TPA ranged from 200 to 1220 and averaged 500, QMD ranged from 5.0 to 11.2 inches and averaged 7.7, and basal area ranged from 93 to 255 square feet per acre and averaged 171. When using an exponent of 1.6 for equation (1), SDI ranged from 205 to 434 and averaged 329.

MSDR Species Boundary Line b Estimation Methods

Mean slope calculation method—Rather than using regression analysis techniques, an estimated value of the MSDR species boundary line b can be obtained by determining the arithmetic mean of all successive slopes from individual plots at the MSDR stage of stand development:

$$b = (LnTPA_{t+3} - LnTPA_t)/(LnQMD_{t+3} - LnQMD_t) \quad (2)$$

where:

$LnTPA_{t+3}$–LnTPA at the successive measurement (all plots were remeasured on 3 year intervals)
$LnTPA_t$–LnTPA at the current measurement (t)
$LnQMD_{t+3}$–LnQMD at the successive measurement
$LnQMD_t$–LnQMD at the current measurement (t)

Equation (2) quantifies the change in LnTPA given a change in LnQMD—the b in equation (1). The Mean slope calculation method is used in this paper only as a "reality check" for the estimated b's using the other statistical methods.

Ordinary least squares—Several researchers have used either linear or non-linear regression to estimate the MSDR species boundary line b (Bredenkamp and Burkhart 1990, Hynynen 1993, MacKinney and Chaiken 1935, Oliver and Powers 1978, Smith and Hann 1984, Williams 1996, Wittwer and others 1998, Yang and Titus 2002). For this paper, the OLS form will be used:

$$LnTPA = b_0 + b_1 LnQMD + \epsilon \quad (3)$$

where:
b_0, b_1 = parameters to be estimated where b_1 = b from equation (1).
ϵ = random error where it is assumed $\epsilon \sim N(0, \sigma^2 I)$.
When using OLS to estimate the MSDR species boundary line b, individual MSDR dynamic thinning line b's are ignored. OLS, and the commonly used form of non-linear regression (e.g., when not directly accounting for autocorrelation among observations) to estimate the MSDR species boundary line b do not account for correlations among observations from individual stands. For OLS, Proc Reg of the SAS Institute (SAS 1996) was used to estimate MSDR species boundary line b's.

First-difference model—Wittwer and others (1998) and Lynch and others (2004) used a first-difference approach to account for dependencies among observations from the same stand (or plot) when determining the MSDR species boundary line b. A first-difference model is expressed as:

$$LnTPA_{t+3} - LnTPA_t = b(LnQMD_{t+3} - LnQMD_t) + \epsilon \quad (4)$$

where:

b is a parameter to be estimated and is equivalent to the b from equation (1).
ϵ = random error where it is assumed $\epsilon \sim N(0)$.

In this study, the youngest observation occurring along an individual MSDR dynamic thinning line boundary was not included in the first-difference model analysis since the lag of LnTPA and lag of LnQMD did not exist along the MSDR dynamic thinning line boundary (fig. 2A). Thus, the sample size for this particular method is the same as the Mean slope calculation method and is less than the OLS and linear mixed effects model analyses. Parameter estimates were obtained using Proc MODEL of the SAS Institute (SAS 1988).

Linear mixed effects model—Although a first-difference model accounts for autocorrelation between successive measurements from the same plot, it fails to account for autocorrelation among many observations from the same plot. Linear parametric mixed effects analyses can account for correlation among many observations from the same plot (Lappi and Bailey 1988, Schabenberger and Pierce 2002, pg. 408). Hynynen (1993) used a mixed effects analysis to estimate the MSDR species boundary line b but did not report an OLS estimated value and thus it cannot be determined whether the two statistical methods produced similar estimates of the MSDR species boundary line b.

$$LnTPA = (b_0 + u_{0i}) + (b_1 + u_{1i})LnQMD + \epsilon \quad (5)$$

where:
u_{0i}, u_{1i} = are cluster-specific random effects to be predicted and assumed to be $N(0, \sigma_0^2)$ and $N(0, \sigma_1^2)$, respectively. A cluster is an individual plot (indexed by *i*).
ϵ = random error where it is assumed $\epsilon \sim N(0, \sigma^2 I)$.

For this analysis, the intercept (b_0) and b (b_1 is the MSDR species boundary line slope) terms from equation (3) were assumed to be random parameters (each individual plot, or cluster, has its own intercept and slope). Estimated parameters were obtained using Proc Mixed of the SAS Institute (SAS 1988). For all analyses, an "unstructured" random effects covariance-variance matrix (un) was used in Proc Mixed; thus the data were used to estimate the entire covariance-variance structure ($\sigma_0^2, \sigma_1^2, \sigma_{01}$).

Stability of the Estimated MSDR Species Boundary Line b in Relation to Site Quality

For this paper, stability refers to the extent to which parameter estimates do not change when the range of site indices in the fitting dataset changes. In order to see how including different site indices can affect the estimated value of the MSDR species boundary line b for a particular statistical method, several analyses were conducted. First, observations from MSDR dynamic thinning lines of all site qualities were included to estimate the MSDR species boundary line b using the four statistical methods. Second, to determine if site index affects the estimated value of the MSDR species boundary line b, estimated b's were obtained from datasets containing all site indices greater than 50, 55, and 60 feet. These categorical values result in nearly equal decreases in sample sizes while also providing sufficient numbers of observations to estimate the MSDR species boundary line b.

RESULTS

Estimates of the MSDR species boundary line b are given in table 1. The OLS parameter estimates are the least stable as the range of site indices included in the dataset change. This instability apparently results from the lack of independence of observations. Based on residual and lag residual plots, the data used in this study have a strong presence of positive autocorrelation. When using the first-difference model the autocorrelation was reduced.

The linear mixed effects analysis produces relatively stable estimates of b as site index changes (b ranges only from -1.6639 to -1.5537 when including different site qualities). This statistical method seems to be robust against factors such as site quality that can change the MSDR dynamic thinning line boundary producing unstable MSDR species boundary line b estimates when using OLS (e.g., -1.7626 to -1.4593). The first-difference model also produced relatively stable estimates of b as site index changed (b ranges only from -1.6266 to -1.5792 when including different site qualities).

DISCUSSION

Some may argue this paper deals with estimating the b of the MSDR species boundary line and thus accounting for MSDR dynamic thinning lines is not necessary. If all we wanted to know was the maximum TPA for a given average tree size across all loblolly pine plantations in the Southeastern US then the OLS estimated b would be appropriate. However, beyond determining the maximum TPA for a given average tree size, it is often desired to quantify how, on average, maximum TPA changes for a given change in average tree size for individual plantations – this can also be thought of as the b of equation (1). As seen in table 1 and fig. 2B, the OLS estimated b provides a quantification of the upper boundary of the relationship between average tree size and tree density. However, this b fails to adequately describe

Table 1—Estimates of the MSDR species boundary line slope (b) using several statistical methods for the full dataset and for subsets of the data consisting of varying site indices

Site index	Estimation method	n	Intercept	Std. error	b	Std. error
>50	OLS	300	9.3981	0.1141	-1.5563	0.0554
	First	185	-	-	-1.6071	0.0237
	Mixed	300	9.4611	0.0597	-1.5858	0.0292
	Mean	185	-	-	-1.5669	0.0247
>55	OLS	186	9.2490	0.1614	-1.4850	0.0772
	First	113	-	-	-1.5831	0.0267
	Mixed	186	9.5078	0.0723	-1.6049	0.0352
	Mean	113	-	-	-1.5588	0.0284
>60	OLS	81	9.8398	0.2384	-1.7626	0.1117
	First	47	-	-	-1.6266	0.0440
	Mixed	81	9.6361	0.1106	-1.6639	0.0553
	Mean	47	-	-	-1.6037	0.0479
All	OLS	365	9.1848	0.0996	-1.4593	0.0490
	First	226	-	-	-1.5792	0.0212
	Mixed	365	9.3791	0.0539	-1.5537	0.0259
	Mean	226	-	-	-1.5522	0.0223

Std. error—standard error of the estimate, OLS—Ordinary Least Squares method, First—First-difference model method, Mixed—Linear mixed effects model method, Mean—Mean slope calculation method .

the expected population change (based on the Mean slope calculation method) in maximum TPA given a change in average tree size. Growth and yield models are often constrained using the MSDR species boundary line or the Self-thinning rule. In many cases, based on the data used in this analysis and analyses conducted by VanderSchaaf and Burkhart (2007), the estimated OLS b would, on average, incorrectly predict stand development. A few MSDR dynamic thinning lines may have a b close to the estimated OLS b though.

Why is the OLS Estimated b Not Sufficient For Describing MSDR Dynamic Thinning Lines?

Trajectories of stands with lower site indices generally fall short of the MSDR species boundary line when using a b near –1.6 if the MSDR species boundary line is established using greater site indices. It has been reported the maximum tree density obtainable for a given average tree size is less on lower quality sites (Strub and Bredenkamp 1985, Harrison and Daniels 1988, Hynynen 1993, Pittman and Turnblom 2003). Thus, MSDR dynamic thinning line boundaries of varying site indices may not always occur at the MSDR species boundary line when using a b near -1.6. For the data used in this study, MSDRs were found to vary across site index. To account for differences in MSDR dynamic thinning line boundaries, in addition to adjusting the intercept, OLS adjusts the MSDR species boundary line b (table 1 and fig. 1).

From a statistical point of view, the OLS estimated MSDR species boundary line b fails to adequately describe, on average, the b of MSDR dynamic thinning lines because it fails to account for correlation among observations from the same stand. By assuming all observations from MSDR dynamic thinning lines are independent, OLS does not estimate the MSDR species boundary line b taking into account that MSDR dynamic thinning line boundary levels differ in relation to site index (e.g., fig. 1). Perhaps many studies that have found a large difference between their estimated MSDR species boundary line b and Reineke's original value of -1.605 (or MacKinney and Chaiken's value of -1.707) should be reexamined using mixed models.

For the data used in this study and when using the mixed effects estimate of the MSDR species boundary line II b for the entire dataset (-1.5537), lower site indices were found to have a lower maximum SDI (SDI = 266.1065 +1.190794SI, R-square = 0.0321) similar to Strub and Bredenkamp (1985). As compared to planting density (VanderSchaaf and Burkhart 2007), site quality appears to have a less drastic affect on estimated MSDR species boundary line b's for loblolly pine plantations (table 1). This may potentially be due to the fact that site quality has less impact on MSDR dynamic thinning line boundary levels. However, planting density and genetics are confounding factors in this study. The data used by VanderSchaaf and Burkhart (2007) were obtained from sites basically having the same site quality and of the same genetic stock. Thus, site quality may have just as much impact as planting density on loblolly pine plantation MSDR dynamic thinning line boundary levels and estimated MSDR species boundary line b's.

When comparing the stability of the linear mixed effects model to the first-difference model, both methods produce relatively stable estimates of the MSDR species boundary line II b. In fact, unlike for planting density (VanderSchaaf and Burkhart 2007), the first-difference model appeared to be more stable than the mixed effects model. However, when comparing estimates from the two models to the Mean slope calculation method, both appear to give reasonable estimates. Actually, for most datasets, a linear mixed effects model will likely be superior because the estimated MSDR species boundary line II b value will be based on accounting for autocorrelation among all observations for a particular MSDR dynamic thinning line boundary. Although the Mean slope calculation method was used as the "reality check," in fact, the linear mixed effects method may be superior to both equations (2) and (4) when estimating the MSDR species boundary line II b. Based on the mixed effects analysis, the predicted MSDR dynamic thinning line b's ranged from -2.1748 to -1.1929 –- this range is similar to other reported studies (Pretzsch and Biber 2005).

CONCLUSIONS

Site quality can impact MSDR dynamic thinning line boundary levels causing instability in MSDR species boundary line b estimates. By using mixed models, more stable estimates can be obtained and the impact of site quality on the b estimate can be reduced. Based on the data used in this analysis and the linear mixed effects analysis for the entire dataset (n = 365), and the analyses by VanderSchaaf and Burkhart (2007), foresters some 70 years ago (MacKinney and Chaiken 1935, Reineke 1933) may well have determined the population average MSDR dynamic thinning line b for loblolly pine stands throughout the Southeastern US. Results from this study suggest quantifying MSDR dynamic thinning line boundaries and b's will provide a better description of maximum tree density–average tree size relationships for individual plantations.

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Hardwood Intermediate Treatments

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FORESTED LAND COVER CLASSIFICATION ON THE CUMBERLAND PLATEAU, JACKSON COUNTY, ALABAMA: A COMPARISON OF LANDSAT ETM+ AND SPOT5 IMAGES

Yong Wang, Shanta Parajuli, Callie Schweitzer, Glendon Smalley, Dawn Lemke, Wubishet Tadesse, and Xiongwen Chen[1]

Abstract—Forest cover classifications focus on the overall growth form (physiognomy) of the community, dominant vegetation, and species composition of the existing forest. Accurately classifying the forest cover type is important for forest inventory and silviculture. We compared classification accuracy based on Landsat Enhanced Thematic Mapper Plus (Landsat ETM+) and Satellite Pour l'Observation de la Terre (SPOT5) images for three land cover types (mixed oak forest, mixed hardwood forest, and agricultural) of the Cumberland Plateau, Jackson County, northern AL. The overall accuracy was 67 and 71 percent based on Landsat ETM+ and SPOT5 images, respectively. The most obvious commission error (misclassifying into wrong categories) was caused by mixed hardwood forest using SPOT-5 image and mixed oaks forest using Landsat ETM+ image, each was about 35 percent. The high omission error (omitting from correct categories) was associated with SPOT-5 data for the mixed hardwood and mixed oak forest. The low accuracy is typical for areas dominated by deciduous forest. Future research needs to explore the possibility of incorporating other GIS data such as variables derived from digital elevation model to improve the classification accuracy.

INTRODUCTION

Forest cover classifications focus on the growth form (physiognomy) of the community, dominant vegetation, and species composition. The information is often used for forest inventory, sustainable management of forest resources, and conservation of biodiversity associated with the forest. Accurate classification of forest cover types can help forest resource managers to maker better decisions. Traditionally, forest cover classifications and mapping have been done by interpreting aerial photos or ground surveys. Forests are often complex; vary by topographic, edaphic, and climatic conditions; and are under constant change because of natural and human disturbances. Traditional forest classifications and mapping are time-consuming and cost-intensive. Over the last twenty years geographic information system (GIS) and remote sensing date have become important tools to generate digital maps and database of current forest types.

It has been demonstrated that visual and digital analysis based on Landsat Enhanced Thematic Mapper (Landsat ETM+) images (30 m resolution) could yield land cover maps useful for forest management purposes (Apan 1997, Sotomagor 2002). Although successful in many instances, forest cover classification based on Landsat ETM+ images still presents several difficulties particularly with complex topographic landscapes and among hardwood forest cover types. While the sun and viewing angles can be considered constant within an image, the topographic characteristics of the terrain may change the illumination geometry, affect spectral signatures of a cover type, and cause classification errors in the spectral classification (Holben and Justice 1980, Civo 1989). To address this problem, Madden (2003) used the elevation, slope, and aspect generated from Digital Elevation Model (DEM) to assist the vegetation classification based on Landsat ETM+ data, and achieved 75 percent classification accuracy; Fahsi and others (2000) used same technique and found classification accuracy increased by incorporating DEM data. Classification of deciduous hardwood forest cover types has shown difficulty with Landsat ETM+ data because the dominant deciduous tree species of different forest often have similar spectral signatures (Jensen 2002, Schriever and Congalton 1995). Czaplnewski and Patterson (2003) found that there was a geometric increase in the error rate as the number of forest strata in the classification system increased.

Recent development and availability of high resolution satellite image from Satellite Pour l'Observation de la Terre (SPOT) provides an opportunity to extract more ground information that was not extracted by LANDSAT. An important factor limiting classification accuracy at higher levels of detail is the spatial resolution of the sensor system used. According to Jensen (2004), typically, sensors such as LANDSAT could be successfully used for classification at Anderson Level I (forest vs. non-forest) and classification at Anderson Level II (evergreen forest, deciduous forest, and mixed forest) requires higher resolution sensors like SPOT5 multispectral (10 m resolution). The SPOT satellites' unique features, variable viewing geometry, stereo imaging, and frequent revisit capability provide a flexible platform for capturing imagery on request and opportunities to get more detailed information of the land cover at a specific time period. Using SPOT data, Williams (1992) found that the accuracy of classifying 16 non-forest, 6 forested, and 6 other land cover types of the Peter Lougheed Provincial Park of the Kananaskis Valley in southwest Alberta, Canada was improved compared to classifications based on LANDSAT data. However, May and others (1997) found that LANDSAT data was more effective than SPOT data in separating shrubs

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from meadows, but neither LANDSAT nor SPOT data were effective for separating meadow types.

The land cover of Cumberland Plateau region of northern AL is dominated by oak-hickory hardwood forest with mixed oak forest occurring above the escarpment and mixed hardwood forest occurring mainly below the escarpment (Smalley 2003). The landform is complex and varies both in elevation and aspect. These features of the study area suggest that reliable classification of land cover for this area could be difficult to achieve using remotely sensed data and no such study exists for this area. In this study, we attempted to classify the land cover of two locations at Jackson County, AL. Our specific objectives were to (1) classify the land cover using remotely sensed data and (2) compare the accuracy of land cover classifications based on LANDSAT TM and SPOT5 images.

METHODS

Study Area

This research focused on Jackson County of northern AL. We selected two sites in the northern Jackson County: the Hytop (34°56'30"N, 86°04'00"W) and Estill Fork (34°58'30"N, 86°12'30"W) tracts (fig. 1) both within the strongly dissected southern sub-region of the Mid-Cumberland Plateau Ridge (Smalley 1982). The region has temperate climate characterized by long, moderately hot summers, and short, mild winters due to the region's proximity to the Gulf of Mexico. The mean temperature for the region is about 13 °C. Precipitation is heavy throughout the year with some periods of prolonged droughts (Smalley 1982).

Remote Sensing Data Pre-processing and Classification

We acquired Landsat ETM$^+$ images of October 20, 2003 and SPOT-5 multispectral image of October 18, 2005. The images were first geo-referenced by identifying ground control points on each image and on the topographic map used as a reference map. The images were further georeferenced using digital orthophotographs with six reference points such as roads, crossroads, and waterways that were identified on both sources. The final images had rooted mean square error (RMS) < 50 percent of the pixel size. The image was then referenced to Universal Transverse Mercator (UTM) projection (Zone 16), NAD 83 coordinate system. The supervised maximum likelihood classification algorithm was used to separate the land cover to three major land covers: mixed oak forest, mixed hardwood forest, and agriculture (including pastures) based on signatures from *in situ* ground cover data and aerial photographs. Earth Resource Data Analysis (ERDAS) Imagine 8.7 software was used for image data pre-processing and classifications.

Accuracy Assessment

The accuracy assessment was accomplished by comparing the classification results based on the images with the land cover type collected in the field. First, ninety-eight random points were first generated on the classified image and their geographic locations (longitude and latitude) were recorded. These random points were then located in the field using global position system (GPS) and the land types were identified. Deciduous forests were classified as mixed oak forest when oaks contributed $\geq$ 80 percent total basal area and mixed hardwood forest otherwise (modified from Smalley 1982). The land cover types of these random points from the field were compared with their classification type from image analysis, and an error matrix was then generated to assess the accuracy level (Rosenfield and Fitzpatrick 2001). Overall accuracy, producer accuracy, and user accuracy were calculated (Jensen 2004). Overall accuracy is the probability of correct classification of the image with respect to the reference data. The probability that a sample from the classified image actually represents that class in the reference (field) data is the producer accuracy. The probability that a reference sample is correctly classified by imagery analysis is the user accuracy. We also used the Kappa coefficient to assess the agreement between the classifications generated based on images and from field survey. The Kappa coefficient (Bishop and others 1975) is based on

$$K = [N\sum x_{ij} - \sum (x_{i+} \times x_{+i})] / [N^2 - \sum (x_{i+} \times x_{+i})] \qquad (1)$$

where K is the Kappa coefficient, N is the total number of pixels in the error matrix, X_{ij} is the number of observations in row i and column j, and X_{i+} and X_{+i} are the marginal total of the error matrix table for row i and column j, respectively.

RESULTS AND DISCUSSION

LANDSAT Classifications

The overall classification accuracy was 67 percent based on the Landsat ETM$^+$ images (table 1). The agricultural land had the lowest user accuracy (50 percent) and the highest producer accuracy (100 percent), which indicates that the agriculture lands could be misclassified as forests, but forests were never misclassified as agriculture land. Producer accuracy was similar between the mixed oak forest (72 percent) and mixed hardwood forest (70 percent). The highest user accuracy was for the mixed hardwood forest (77 percent) compared to 64 percent of mixed oak forest, suggesting that mixed oak forest was more likely to be misclassified to mixed hardwood forest. Kappa coefficient was 49 percent for land covers combined, was the highest for mixed hardwood forest (55 percent), and the lowest (44 percent) for the agriculture land cover. The mixed hardwood was the most abundant cover type (4 402 ha) in the study area followed by mixed oak forest (table 2).

SPOT-5 Classification

The overall classification accuracy was improved to 71 percent (table 1) based on SPOT-5 images. However, the producer accuracy decreased for both forest covers, and did not change for agriculture land. User accuracy was increased for mixed oak forest (from 64 to 72 percent), decreased for agriculture land (from 100 to 82 percent) and mixed hardwood forest (from 77 to 65 percent). Overall Kappa coefficient was 53 percent. The Kappa coefficient was almost doubled for agriculture land, increased 4 percent for mixed oak forest, and reduced 16 percent for mixed hardwood forest

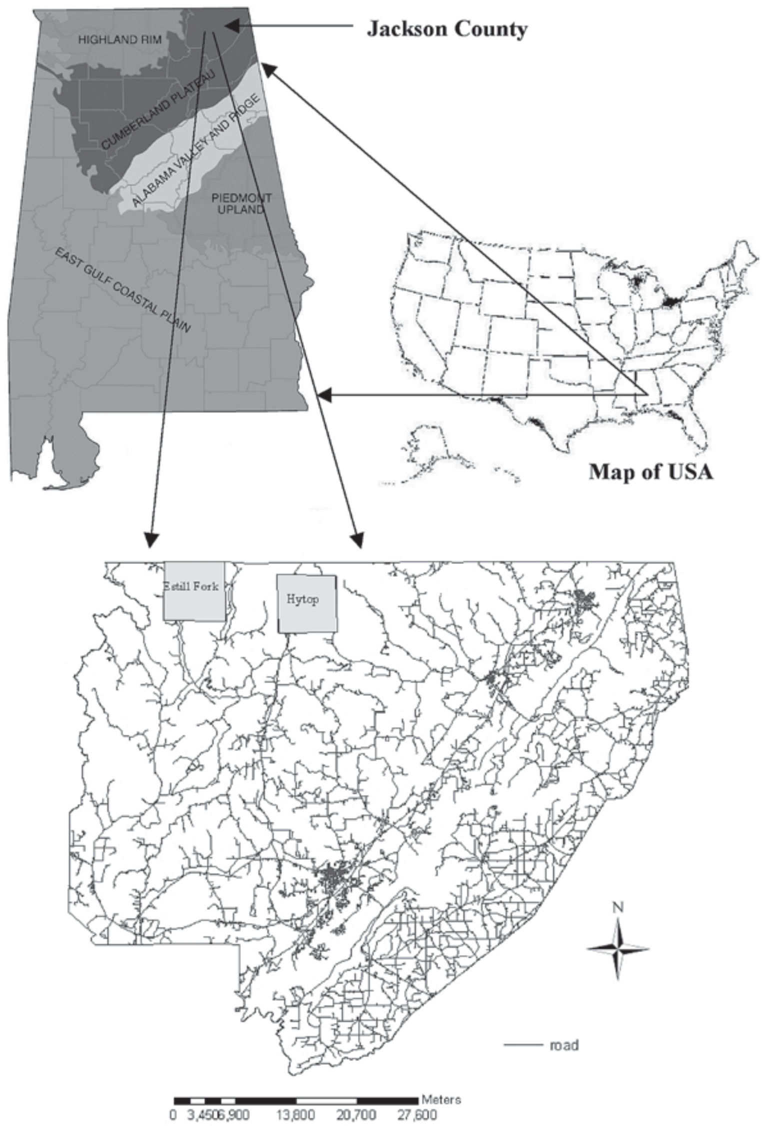

Figure 1—Hytop and Estill Fork study sites in the northern Jackson County, Alabama, USA.

Table 1—Accuracy of the land cover classification based on Landsat ETM+ and SPOT5 images of Cumberland region of Jackson County, AL

	Landsat ETM+				SPOT5			
Class	PA[1]	UA	Kappa coefficient[2]	OA	PA	UA	Kappa coefficient	OA
Mixed oak forest	72	64	46	67	65	72	50	71
Mixed hardwood	70	77	55		67	65	39	
Agriculture and pasture	100	50	44		100	82	78	

[1] PA is the producer accuracy, UA is the user accuracy, and OA is the overall accuracy in percentages.
[2] Kappa coefficient measures the agreement between the classifications based on remotely sensed images and the reference points from the field, higher values indicate greater agreement.

Table 2—Total area calculated for each land cover type using Landsat ETM+ and SPOT5 for the study sites of the Cumberland region of Jackson County, AL

Class	Landsat ETM+ Area (ha)	Landsat ETM+ Percent	SPOT5 Area (ha)	SPOT5 Percent
Mixed oak forest	3790	44	3641	43
Mixed hardwood	4402	52	4673	55
Agriculture and pasture	327	4	205	2

compared to the classification from Landsat ETM+ data. The results suggest that with the higher resolution of SPOT-5 image, the agricultural lands and mixed oak forest were more likely to be accurately identified while the accuracy for mixed hardwood forest was lower compared to the classification based on Landsat ETM+. The area estimated based on SPOT5 image decreased from 327 ha to 205 ha (a 37.3 percent reduction) for agriculture land and increased from 4402 ha to 4673 ha for mixed hardwood forest (a 5.8 percent increase) (table 2).

CONCLUSIONS

The use of SPOT5 images for classifying land cover of the Cumberland Plateau of Jackson County, AL, a landscape dominated by deciduous hardwood forest, improved classification accuracy compared to the classification based on Landsat ETM+. However, the accuracy of the classification based on Landsat ETM+ and SPOT5 data was relatively low (about 70 percent) and below the Anderson criterion (80 percent) for image application. This is typical for areas dominated by deciduous forest (Jensen 2002, Schriever and Congalton 1995). Hardwood forests are difficult to distinguish because of similar vegetation components and hence, the spectral similarity (Jensen 2002). The most obvious commission error (misclassifying to wrong categories) was caused by mixed hardwood forest using SPOT-5 image and mixed oaks forest using Landsat ETM+ image, each was about 35 percent. The high omission error (omitting from correct categories) was associated with SPOT-5 data for the mixed hardwood and mixed oak forest.

We classified forest type based the criteria of mixed oak forest (forests with ≥ 80 percent oaks) and mixed hardwood (forest with < 80 percent oaks). According to Smalley (1982), mixed oak forests contain primarily white oak (*Quercus alba* L.), scarlet oak *(Q. coccinea* Muench.*),* southern red oak (*Q. falcata* Michx.), black oak (*Q.velutina* Lamarck), chestnut oak (*Q. prinus* L.), and have associations with hickories (*Carya spp*.), black gum (*Nyssa sylvatica* Marsh.), red maple (*Acer rubrum* L.), shortleaf pine (*Pinus echinata* Mill.), and Virginia pine (*P. virginiana* Mill.); they occupy the drier sites on top of the Plateau including ridges above the base level of the plateau and on the upper warm escarpment slopes. In places, shortleaf and Virginia pines are prevalent on upper warm escarpment slopes perhaps reflecting a fire history. Mixed hardwoods (i.e., greater percentage of species other than oaks) are on the more moist sites on top of the plateau, in stream channels, on cool slopes above the base level of the plateau, and on the warm upper escarpment slopes (Smalley 1982).The lower escarpment slopes are sometimes an Eastern redcedar (*Juniperus virginiana* L.)-hardwood mixture. Under natural environmental conditions, there are gradations between all of these vegetation types, reflecting the variations in geophysical features such as elevation, slope, and relief. This could result in the errors of our classification with Landsat ETM+ and SPOT5 images.

Managers of Southern United States forests are under increasing pressure to balance the economic, social, and ecological aspects of the resource. Meeting contemporary demands for healthy forests as well as forest products depends on increasing productivity while protecting the environment and sustainability of the forests. The accurate inventory of different forest covers in a timely manner is critical. Remote sensing and GIS-based classification such as those from this study can provide quick and relatively inexpensive mapping and quantitative estimation of forest covers. Further study will explore the possibility of incorporating other GIS data such as those variables derived from digital elevation model for image analysis to improve the classification accuracy.

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STAND QUALITY MANAGEMENT OF A WATER OAK PLANTATION IN LOUISIANA: PRELIMINARY RESULTS FOLLOWING THINNING

James S. Meadows and Daniel A. Skojac, Jr.[1]

Abstract—Stand quality management is a new guiding principle in which thinning prescriptions are based on tree quality rather than on residual stand density. We recently initiated a series of hardwood thinning studies to determine the effects of four stand quality management thinning prescriptions on both stand-level and individual-tree-level growth, quality, and value: (1) no thinning, (2) Acceptable with Superior Poletimber, (3) Acceptable with No Poletimber, (4) Desirable with Superior Poletimber, and (5) Desirable with No Poletimber. The first study was installed during the summer of 2004 in a 35-year-old water oak (*Quercus nigra* L.) plantation at the Red River Wildlife Management Area near Shaw, LA. Prior to thinning, stand density averaged 122 trees and 101 square feet of basal area per acre. Quadratic mean diameter of the stand was 12.4 inches. All four thinning prescriptions significantly increased diameter growth of individual water oak trees during the first two years after thinning. However, thinning also stimulated the production of new epicormic branches on the butt logs of residual trees. The Acceptable with Superior Poletimber thinning prescription produced the best combination of (1) acceptable residual stand density, (2) improved diameter growth, and (3) least adverse effect from the production of epicormic branches in this previously unmanaged, mid-rotation water oak plantation.

INTRODUCTION

Profitable management of hardwood stands for sawtimber production demands not only satisfactory rates of tree growth, but also requires the development and maintenance of high-quality, high-value logs. Thinnings often are used to fulfill these goals. Specifically, thinnings in southern bottomland hardwood stands should be designed to improve growth of residual trees and to maintain and enhance bole quality of residual trees (Meadows 1996).

Thinning regulates stand density and increases diameter growth of residual trees, as has been reported for several hardwood forest types in the Eastern United States (Hilt 1979, Lamson and Smith 1988, Sonderman 1984a). Generally, diameter growth of residual trees increases as thinning intensity increases. However, recent research in natural, mixed-species, bottomland hardwood stands indicates that residual dominant and codominant red oaks (*Quercus* spp.) exhibit similar diameter growth responses to thinnings in which residual stand densities range from 64 to 86 square feet of basal area per acre (Meadows and Goelz 2002, Meadows and Skojac 2006). Significant increases, of nearly identical magnitude, in diameter growth of these valuable red oaks can be achieved through thinning, as long as residual stand density falls within this fairly broad range.

However, over-thinning may reduce residual stand density to the point where stand-level basal area growth and volume growth are greatly diminished, even though diameter growth and volume growth of individual residual trees are greatly enhanced. Minimum residual density levels necessary to maintain satisfactory stand-level growth after thinning have been reported for different types of upland hardwood stands (Hilt 1979, Lamson and Smith 1988), but no recommended minimum residual stand density levels have been identified for southern bottomland hardwood stands. Meadows and Goelz (2001), however, observed that a residual basal area of 52 square feet per acre in a 28-year-old water oak (*Quercus nigra* L.) plantation was sufficient to promote adequate stand-level growth following thinning, but that a residual basal area of 34 square feet per acre created severely understocked conditions that likely will depress stand-level growth for many years.

Degradation of bole quality, specifically in the form of increased production of epicormic branches along the boles of residual trees, often occurs as a result of thinning in hardwood stands. For example, Sonderman (1984b) found that the number and size of epicormic branches on the boles of upland oak trees increased significantly as residual stand density decreased. However, this adverse effect of thinning on bole quality most often is associated with poorly planned thinning operations, in which high-value trees are harvested to provide income for the landowner and low-value trees are retained to form the residual stand. This form of high-grading is not conducive to profitable management of hardwood stands for high-quality sawtimber production.

In contrast, well-designed hardwood thinning operations strive to increase the proportion of high-value trees and to decrease the proportion of low-value trees. Trees that are damaged or diseased, have low-quality boles, or are undesirable species should be removed; trees that are healthy, have high-quality boles, and are desirable species should be retained. Because thinning should favor healthy, sawtimber-sized trees of desirable species, the proportion of dominant and codominant trees in the residual stand typically increases as thinning intensity increases. Vigorous, upper-crown-class trees are much less likely to produce epicormic branches than are less vigorous, lower-crown-class trees (Meadows 1995). Consequently, production of epicormic branches along the boles of residual trees actually may decrease as thinning intensity increases (Sonderman and Rast 1988). In fact, well-designed thinnings should improve average bole quality throughout the residual stand.

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Stand Density Management
Traditionally, thinning operations in southern hardwood stands are guided by the practice of stand density management. The stand is marked to a predetermined level of residual stand density. Trees to be removed and trees to be retained are selected on the basis of individual tree quality and value. Goelz and Meadows (1997) provided guidelines for the implementation of stand density management in southern bottomland hardwood stands. A stocking guide developed by Goelz (1995) for natural stands of southern bottomland hardwoods forms the basis for these guidelines. In the practice of stand density management, thinnings are designed to reduce stocking to the B-line, which, as described by Goelz (1995), represents the desired level of stocking to be retained after thinning, as recommended by Putnam and others (1960). The B-line ranges from 55 to 60 percent of maximum full stocking in poletimber stands (average diameter of 9 inches) to 80 to 85 percent of maximum full stocking in large-sawtimber stands (average diameter of 30 inches). The first commercial thinning in most natural stands of southern bottomland hardwoods is conducted when average diameter reaches 12 to 14 inches. The corresponding B-line for this stand is 65 to 70 percent of maximum full stocking, equivalent to a residual stand density of 75 to 85 square feet of basal area per acre (Goelz 1995). A reasonable thinning prescription under the guiding principle of stand density management thus might be to thin the stand to a target residual density of 80 square feet of basal area per acre.

The practice of stand density management leads to two serious problems. First, it is difficult for the timber marker to accurately and consistently visualize the prescribed residual density as he/she marks the stand. Second, the timber marker often is forced to either leave low-quality trees or cut high-quality trees in order to maintain the target residual density uniformly across the stand. Consequently, overall stand quality and value frequently are compromised by strict adherence to stand density management.

Stand Quality Management
Due to the problems associated with stand density management, and because bole quality and species play such significant roles in setting the value of hardwood timber, we recently developed the concept of stand quality management as the new guiding principle for management of southern hardwood forests. The basic tenet of stand quality management is that the stand should be managed to maintain a high level of residual stand quality, with residual stand density relegated to a role of secondary importance. In its simplest terms, stand quality management is expressed as "If it's a good tree, leave it; if it's a poor tree, cut it!" Less emphasis is placed on the idea that hardwood stands must be thinned to a target level of residual stand density. Rather, quality dictates which trees will be cut and which trees will be left during a thinning operation. As long as residual stand density falls within fairly broad limits, prescriptions and marking rules for thinnings are based on tree quality alone.

We also recently developed a new hardwood tree classification system that can be used as a tool to implement stand quality management. Definitions for the tree classes are based on five characteristics that affect future performance and value growth potential of individual hardwood trees: (1) species, (2) crown class, (3) current condition of the tree and future risk of mortality or degrade in merchantability, (4) bole quality, and (5) expected change in value over time.

The first component of our new system consists of five tree classes used only for sawtimber-sized trees, in descending order of desirability and value: (1) preferred growing stock, (2) desirable growing stock, (3) acceptable growing stock, (4) cutting stock, and (5) cull stock. Two additional tree classes are used only for poletimber-sized trees, in descending order of desirability and potential value: (1) superior poletimber stock, and (2) inferior poletimber stock. Trees in the preferred growing stock, desirable growing stock, acceptable growing stock, and superior poletimber stock classes are currently or potentially suitable for the production of high-quality sawtimber and are collectively referred to as "growing stock." Conversely, trees in the cutting stock, cull stock, and inferior poletimber stock classes are unsuitable for the production of high-quality sawtimber and are collectively referred to as the "overburden."

In stand quality management, the quality of each individual tree determines which trees are left and which trees are cut in a thinning operation. The maxim is to leave "good" trees and to cut "poor" trees. Our new tree classification system can be used to identify "good" trees and "poor" trees, and then to segregate them into distinct tree classes. Thinning prescriptions and marking rules are based on tree class alone, such that the tree classes actually define the residual component of four different thinning prescriptions under stand quality management (table 1). Even though most trees removed under stand quality management have low value, the volume removed should be sufficient to warrant a commercial thinning operation, particularly in areas with a viable hardwood pulpwood market.

Selection of the most appropriate thinning prescription to use in any given stand of southern hardwoods depends on two factors: (1) initial stand quality, and (2) stage of stand development. Initial stand quality is estimated from the tree class distribution of the stand prior to thinning, expressed as the proportion of basal area in each tree class. A stand of medium initial quality contains a relatively high proportion of acceptable growing stock trees and a relatively low proportion of preferred growing stock and desirable growing stock trees. This distribution of tree classes is typical of previously unmanaged stands. In contrast, a stand of high initial quality contains a relatively high proportion of preferred growing stock and desirable growing stock trees and a relatively low proportion of acceptable growing stock trees. This distribution of tree classes is typical of previously thinned stands.
We hypothesize that the two "Acceptable" prescriptions (AccSupP and AccNoPole in table 1) are best suited for stands of medium initial quality, whereas the two "Desirable" prescriptions (DesSupP and DesNoPole in table 1) are best suited for stands of high initial quality and may be unsuited for stands of medium initial quality. The decision to retain or to remove the superior poletimber stock trees depends on the stage of stand development, expressed as the length

Table 1—Marking rules for four thinning prescriptions associated with the practice of stand quality management

Thinning prescription		Marking rules
Acceptable With Superior Poletimber (AccSupP)	LEAVE:	preferred growing stock desirable growing stock acceptable growing stock superior poletimber stock
	CUT:	cutting stock cull stock inferior poletimber stock
Acceptable With No Poletimber (AccNoPole)	LEAVE:	preferred growing stock desirable growing stock acceptable growing stock
	CUT:	cutting stock cull stock superior poletimber stock inferior poletimber stock
Desirable With Superior Poletimber (DesSupP)	LEAVE:	preferred growing stock desirable growing stock superior poletimber stock
	CUT:	acceptable growing stock cutting stock cull stock inferior poletimber stock
Desirable With No Poletimber (DesNoPole)	LEAVE:	preferred growing stock desirable growing stock
	CUT:	acceptable growing stock cutting stock cull stock superior poletimber stock inferior poletimber stock

of time remaining in the rotation before final harvest of the stand. The timber marker retains superior poletimber stock trees in early-to-mid-rotation stands because there is ample time left in the rotation for these trees to develop into quality sawtimber. Conversely, the timber marker removes superior poletimber stock trees in late-rotation stands.

Objectives

To evaluate this new concept of stand quality management, we recently initiated a series of thinning studies in hardwood stands across the South. All individual studies within the series use the same experimental design, treatments, and methods. The study reported here is the first in the series. Each individual study within the series is designed to determine how the four thinning prescriptions associated with stand quality management affect (1) stand-level growth, development, yield, and value; and (2) growth and bole quality of individual trees. Results from the entire series of studies will be combined to develop a research-based model that will provide guidance to forest managers in the selection of the most appropriate stand quality management thinning prescription to use in southern hardwood stands with different levels of initial stand quality and at different stages of stand development.

METHODS

Study Area

The study is located on the Red River Wildlife Management Area between the Mississippi River and the Red River in southern Concordia Parish, near the community of Shaw, LA. The land is managed by the Louisiana Department of Wildlife and Fisheries. The Mississippi River mainline levee protects the site from major flooding, but backwater flooding from nearby canals and bayous may occur periodically during the winter and spring.

Soils across most of the study area are Commerce silt loam or Commerce silty clay loam, but there is a relatively small area of Tunica clay that occupies the western portion of the study site. The Commerce soils are somewhat poorly drained, have very high available water capacity, are moderately slowly permeable, and formed from loamy alluvium. The Tunica soil is poorly drained, has high available water capacity, is very slowly permeable, and formed from clayey alluvium deposited over a layer of loamy alluvium. Broadfoot (1976) reported average site indexes for water oak to be 104 feet at 50 years on the Commerce soils and 88 feet at 50 years on the Tunica soil.

The study area is located entirely within a 160-acre water oak plantation. There are also a few planted cherrybark oak (*Quercus pagoda* Raf.) and willow oak (*Q. phellos* L.) trees scattered throughout the plantation, as well as occasional rows of Nuttall oak (*Q. nuttallii* Palmer) and of pecan [*Carya illinoensis* (Wangenh.) K. Koch]. Volunteer individuals that seeded into the plantation are primarily sycamore (*Platanus occidentalis* L.) and sugarberry (*Celtis laevigata* Willd.). The plantation was 35 years old at the time of study installation. There was no evidence of previous harvesting activity in the plantation. Details, such as site preparation, initial spacing, and early cultural treatments, were not documented at the time of plantation establishment.

Plot Design

Plot design follows the recommendations for standard plots for silvicultural research, as described by the U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station (Marquis and others 1990). We applied each treatment uniformly across a 2.0-acre rectangular treatment plot that measures 4 by 5 chains (264 by 330 feet). We established a 0.6-acre rectangular measurement plot in the center of each treatment plot. Each measurement plot is 2 by 3 chains (132 by 198 feet), which provides a 1-chain-wide (66 feet) buffer strip around each measurement plot. The entire study area is 30 acres.

Treatments

Treatments consist of the four thinning prescriptions associated with stand quality management (table 1) and an unthinned control. Trees were retained or removed from the plantation solely on the basis of tree class. All trees assigned to tree classes designated as "leave" for each given prescription were retained; all trees assigned to tree classes designated as "cut" for each given prescription were removed. No consideration was given to residual stand density or to spacing of residual trees. Treatments were assigned randomly to treatment plots after preliminary data, including tree class of each tree, were collected.

Three replications of the five treatments were applied in a randomized complete block design to the 15 treatment plots (experimental units) during early autumn of 2004. A contract logging crew directionally felled all marked trees with a mechanized feller equipped with a continuously running cutting head. Felled trees were topped and delimbed in the woods. Tree-length logs were removed from the woods with rubber-tired skidders.

Measurements

Before assigning treatments, we conducted a preharvest survey to determine initial stand quality and initial stand density on each 0.6-acre measurement plot. We recorded species, diameter at breast height (d.b.h.), crown class, and tree class on all trees ≥ 5.5 inches d.b.h. We defined sawtimber as trees ≥ 12.0 inches and poletimber as trees ≥ 5.5 inches but < 12.0 inches d.b.h. After marking the treatment plots for thinning according to the marking rules associated with each prescription (table 1), we collected additional data on all designated "leave" trees: (1) the number of epicormic branches > 3/8 inches in basal diameter (designated "large" epicormic branches) on the 16-foot-long butt log, and (2) the total number of epicormic branches, regardless of size, on the 16-foot-long butt log. "Large" epicormic branches are counted as defects on logs of all sizes, grades, and species (Rast and others 1973). Basal diameters of epicormic branches were estimated ocularly. We recorded pulpwood merchantable height on all poletimber "leave" trees and sawtimber merchantable height on all sawtimber "leave" trees. We also recorded log grade, as defined by Rast and others (1973), of the 16-foot-long butt log on all sawtimber "leave" trees. We measured total height on the two largest codominant trees on each measurement plot. All heights were measured using a clinometer. Crown class, d.b.h., the number of "large" epicormic branches, and the total number of epicormic branches on the 16-foot-long butt log were measured annually for the first two years after thinning.

RESULTS AND DISCUSSION

Plantation Conditions Prior to Thinning

Prior to thinning, the plantation averaged 122 trees and 101 square feet of basal area per acre, with a quadratic mean diameter of 12.4 inches, among trees ≥ 5.5 inches d.b.h. The plantation contained 3,729 board feet of sawtimber per acre, Doyle scale, and 4.4 cords of pulpwood per acre. Water oak accounted for 84 percent of the trees, 90 percent of the basal area, 80 percent of the pulpwood volume, and 99 percent of the sawtimber volume. Quadratic mean diameter of the water oak component was 12.8 inches. There were no significant differences among treatment plots in any of the preharvest characteristics.

Although the plantation was relatively dense, most dominant and codominant water oak trees appeared healthy and exhibited few symptoms of poor vigor, such as crown deterioration, loss of dominance, or the presence of numerous epicormic branches along the bole. Small gaps created by the death of scattered trees were interspersed throughout the plantation. Generally, conditions indicated that the plantation needed to be thinned, but overall stand health had not yet begun to decline visibly.

Most trees in the plantation prior to thinning had short merchantable boles of relatively low quality. In fact, average merchantable height of sawtimber trees was only 21 feet. For most trees, merchantable height was limited by the base of the live crown, rather than by excessive sweep and/or crook, abundant defects, damage from insects and/or diseases, or other log abnormalities. Many trees had a few epicormic branches large enough to be counted as defects on the butt log. Across all trees in the plantation, we found an average of 3.8 "large" epicormic branches on the butt log, compared to only 1.7 "large" epicormic branches on the butt log of dominant and codominant water oak. Overall bole quality was relatively poor on most trees, primarily due to existing defects in the form of overgrown knots. Approximately 84 percent of all sawtimber trees in the plantation contained Grade 3 butt logs, the least valuable log grade assigned to hardwood factory-lumber logs, as defined by Rast and others (1973). However, several trees with Grade 3 butt logs actually had high-quality boles, but had not yet attained the minimum size requirements for higher-grade logs.

Prior to thinning, only 54 percent of the total plantation basal area and 55 percent of the water oak basal area consisted of trees in the “growing stock” category (preferred, desirable, and acceptable growing stock sawtimber trees plus superior poletimber stock trees). Conversely, 46 percent of the total and 45 percent of the water oak basal area consisted of trees in the “overburden” category (cutting and cull stock sawtimber trees plus inferior poletimber stock trees). The overburden represents a fairly large component in this previously unmanaged water oak plantation. As a general rule, the overburden should account for less than 40 percent of total basal area. Based on the tree class distribution of the plantation prior to thinning and the expected length of time remaining in the rotation, we classified this water oak plantation as an early-to-mid-rotation stand of medium initial quality.

Plantation Development Following Thinning

Treatments were applied during the early autumn of 2004, using the marking rules established in table 1. The Acceptable With Superior Poletimber thinning prescription (AccSupP) reduced stand density to 52 trees and 54 square feet of basal area per acre, increased quadratic mean diameter to 13.8 inches, and reduced sawtimber volume to 2,480 board feet per acre. It removed 57 percent of the trees, 45 percent of the basal area, and 33 percent of the sawtimber volume. The Acceptable With No Poletimber thinning prescription (AccNoPole) reduced stand density to 39 trees and 47 square feet of basal area per acre, increased quadratic mean diameter to 14.8 inches, and reduced sawtimber volume to 2,702 board feet per acre. It removed 68 percent of the trees, 56 percent of the basal area, and 28 percent of the sawtimber volume. The Desirable With Superior Poletimber thinning prescription (DesSupP) reduced stand density to 30 trees and 33 square feet of basal area per acre, increased quadratic mean diameter to 14.2 inches, and reduced sawtimber volume to 1,447 board feet per acre. This more radical treatment removed 76 percent of the trees, 67 percent of the basal area, and 61 percent of the sawtimber volume. The Desirable With No Poletimber thinning prescription (DesNoPole) reduced stand density to 23 trees and 30 square feet of basal area per acre, increased quadratic mean diameter to 15.6 inches, and reduced sawtimber volume to 1,393 board feet per acre. Our most radical treatment removed 82 percent of the trees, 70 percent of the basal area, and 63 percent of the sawtimber volume.

All four thinning prescriptions produced stand characteristics significantly different from the unthinned control. Residual basal areas associated with the two “Acceptable” prescriptions (AccSupP and AccNoPole) were significantly greater than the residual basal areas associated with the two “Desirable” prescriptions (DesSupP and DesNoPole). However, residual basal area did not differ significantly between the AccSupP prescription and the AccNoPole prescription or between the DesSupP prescription and the DesNoPole prescription. The AccSupP and AccNoPole prescriptions produced residual stand densities that closely correspond to the C-10 and C-15 lines of stocking, respectively, as described by Goelz (1997). These two C-lines of stocking represent stands that will achieve B-line stocking, or minimum full stocking, after 10 and 15 years of growth, respectively. In contrast, the DesSupP prescription produced a residual stand density that corresponds to the C-25 line of stocking, as described by Goelz (1997), whereas the DesNoPole prescription resulted in a residual stand density well below the C-25 line of stocking. The C-25 line of stocking represents a stand that will achieve B-line stocking only after 25 years of growth. By definition, all stands below B-line stocking are, at least to some extent, understocked. Goelz (1997), however, asserted that stands at or below the C-20 line of stocking are so severely understocked that immediate regeneration of the stand is recommended.

The two “Acceptable” prescriptions produced residual stands that are suitable for continued management. In contrast, the two “Desirable” prescriptions clearly removed too many trees and reduced stand densities to levels unacceptable for continued management. These results support our initial hypothesis that the “Acceptable” prescriptions are best suited for stands of medium initial quality, such as this previously unmanaged water oak plantation, whereas the “Desirable” prescriptions are best suited for stands of high initial quality, typical of previously thinned stands, and actually may be unsuited for stands of medium initial quality.

Two years after thinning, 1.7 trees per acre died in the unthinned control plots, but none died in any of the thinned plots. Cumulative mortality in the unthinned control plots was 1.5 percent. All mortality occurred as a result of suppression of individual trees, rather than from some type of major disturbance.

Stand-level basal area growth did not differ significantly among the five treatments during the first two years following thinning, but all four thinning prescriptions produced significant increases in quadratic mean diameter, relative to the unthinned control (table 2). However, increases in quadratic mean diameter did not differ significantly among the four thinning prescriptions. Because it is generally too soon to expect significant stand-level responses to thinning, our stand-level results are inconclusive. Speculation on future stand development would be premature.

Diameter Growth of Water Oak Trees

All four thinning prescriptions significantly increased cumulative diameter growth of residual water oak trees during each of the first two years following thinning (fig. 1). In fact, by the end of the second year after thinning, all four prescriptions had more than doubled the diameter growth of residual water oaks, relative to water oaks in the unthinned control plots. Cumulative diameter growth of residual water oaks in the DesNoPole prescription more than tripled—0.74 inches in just two years. However, there were no significant differences in cumulative diameter growth among the four thinning prescriptions through the first two years following thinning.

The data presented in figure 1 include all water oak trees, regardless of tree size or crown class. However, we are more interested in the response of the larger trees in the stand. To

Table 2—Stand conditions 2 years after application of five thinning treatments in a 35-year-old water oak plantation in Louisiana. See table 1 for an explanation of treatment descriptors. Means within a column followed by the same letter are not significantly different at the 0.05 level of probability

Treatment	Trees	Basal area	Cumulative basal area growth	Quadratic mean diameter	Increase in quadratic mean diameter
	no./ac	----------- *ft²/ac* -----------		---------- *inches* ----------	
Control	113 a	105 a	3.5 a	13.0 c	0.32 b
AccSupP	52 b	58 b	4.5 a	14.4 bc	0.58 a
AccNoPole	39 bc	50 b	3.4 a	15.3 ab	0.55 a
DesSupP	30 cd	36 c	2.9 a	14.8 ab	0.62 a
DesNoPole	23 d	33 c	2.8 a	16.3 a	0.73 a

evaluate this response, we separated the data by tree size class—sawtimber versus poletimber (fig. 2). For purposes of this study, we defined sawtimber as trees ≥ 12.0 inches d.b.h. and poletimber as trees between 5.5 and 11.9 inches d.b.h., inclusive.

By the end of the second year after thinning, all four thinning prescriptions had approximately doubled the diameter growth of sawtimber-sized water oaks, relative to sawtimber-sized water oaks in the unthinned control plots (fig. 2). There were no significant differences in cumulative diameter growth among the four thinning prescriptions, but all of them exhibited significantly greater diameter growth than did sawtimber-sized water oaks in the unthinned control plots.

The AccSupP and DesSupP prescriptions more than tripled the diameter growth of poletimber-sized water oaks, relative to water oak poletimber in the unthinned control plots (fig. 2). Cumulative diameter growth did not differ significantly between these two prescriptions. The AccNoPole and DesNoPole prescriptions were not included in this part of the analysis because, by definition, all poletimber trees in these plots were removed from the plantation.

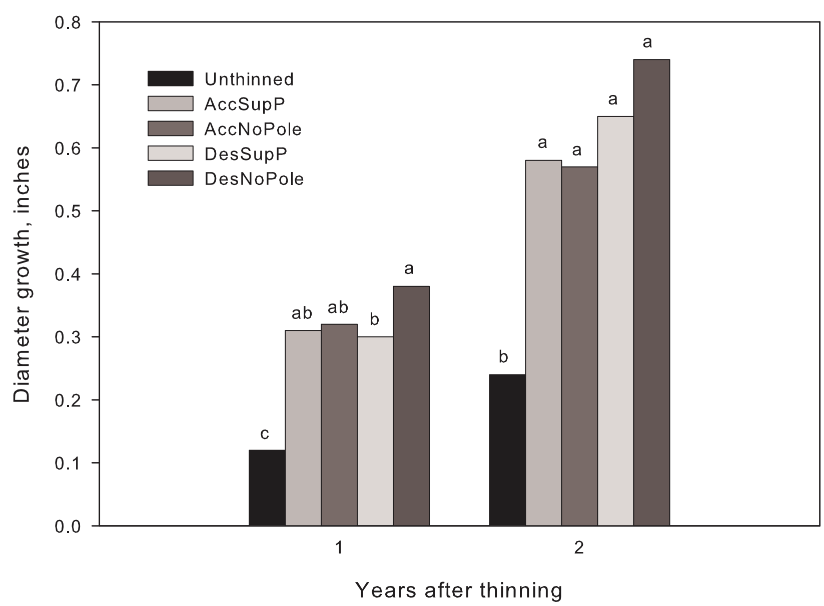

Figure 1—Cumulative diameter growth of residual water oak trees at the end of the first and second years following application of five thinning treatments in a 35-year-old water oak plantation in Louisiana. See table 1 for an explanation of treatment descriptors. Bars within a year followed by the same letter are not significantly different at the 0.05 level of probability.

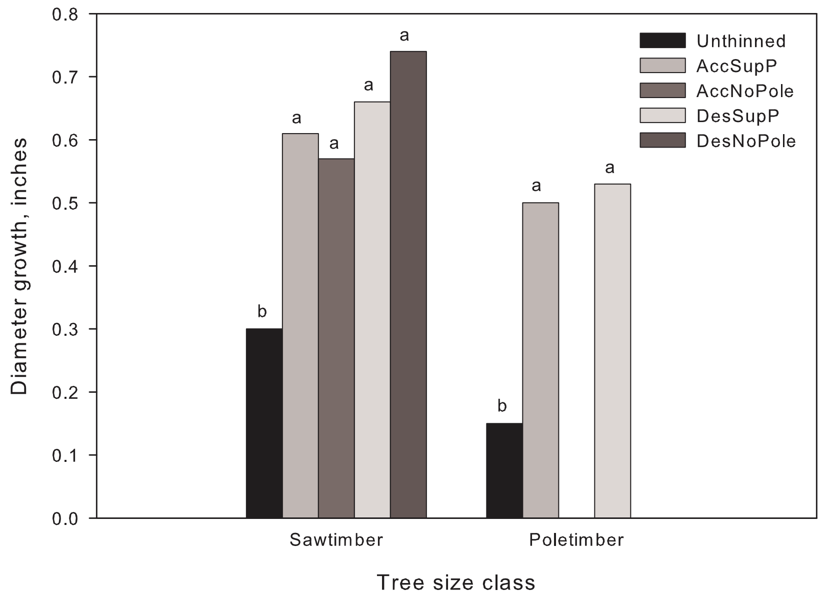

Figure 2—Cumulative diameter growth of residual water oak trees, by tree size class, at the end of the second year following application of five thinning treatments in a 35-year-old water oak plantation in Louisiana. See table 1 for an explanation of treatment descriptors. Bars within a tree size class followed by the same letter are not significantly different at the 0.05 level of probability.

Recent research indicates that diameter growth of residual, dominant and codominant bottomland red oaks following thinning in natural stands is independent of residual stand density, at least within the range of 64 to 86 square feet of basal area per acre (Meadows and Goelz 2002, Meadows and Skojac 2006). It is unknown if the relationship between diameter growth response and residual stand density observed in mixed-species, natural stands also holds true in single-species plantations. Stand dynamics may be quite different between these two types of forests. However, our results in this study generally support the assertion advanced by Meadows and Goelz (2002) and by Meadows and Skojac (2006).

Because all four thinning prescriptions produced stands with residual densities well below the ranges evaluated by Meadows and Goelz (2002) and by Meadows and Skojac (2006), we speculate that differences in residual stand density between the two "Acceptable" prescriptions and the two "Desirable" prescriptions eventually may lead to significant differences in cumulative diameter growth between these two broad types of prescriptions. Using the C-lines of stocking developed by Goelz (1997) as a guide, the residual stands produced through the two "Acceptable" prescriptions are marginally understocked, but still manageable, whereas the residual stands produced through the two "Desirable" prescriptions are severely understocked and should be regenerated. In fact, sawtimber-sized trees retained following "Desirable" thinning are essentially open-grown. As these four stands continue to develop over time, we expect that cumulative diameter growth will be significantly greater on the essentially open-grown, sawtimber-sized, residual water oaks in the "Desirable" stands than on the sawtimber-sized, residual water oaks in the more manageable "Acceptable" stands.

Production of Epicormic Branches on Water Oak Trees

Thinning operations in hardwood stands, while producing positive effects on diameter growth, also may have negative consequences on bole quality of residual trees, particularly in the form of epicormic branches. The production of epicormic branches along the merchantable boles of residual trees can be a serious problem in thinned hardwood stands. Epicormic branches create defects in the underlying wood and can reduce both log grade and subsequent lumber value. In one case study in Alabama, defects from epicormic branches reduced the value of willow oak lumber by 13 percent (Meadows and Burkhardt 2001).

Immediately after thinning, residual water oaks in the thinned plots averaged fewer than two "large" epicormic branches (>3/8 inches in basal diameter) on the butt log, whereas water oaks in the unthinned control plots averaged nearly four branches (fig. 3). These statistically significant reductions in the number of large epicormic branches were the direct result of the thinning operation. All thinning prescriptions discriminated against trees that had numerous pre-existing epicormic branches. Those trees were removed from the plantation during thinning; most trees retained during the thinning operation had few pre-existing epicormic branches.

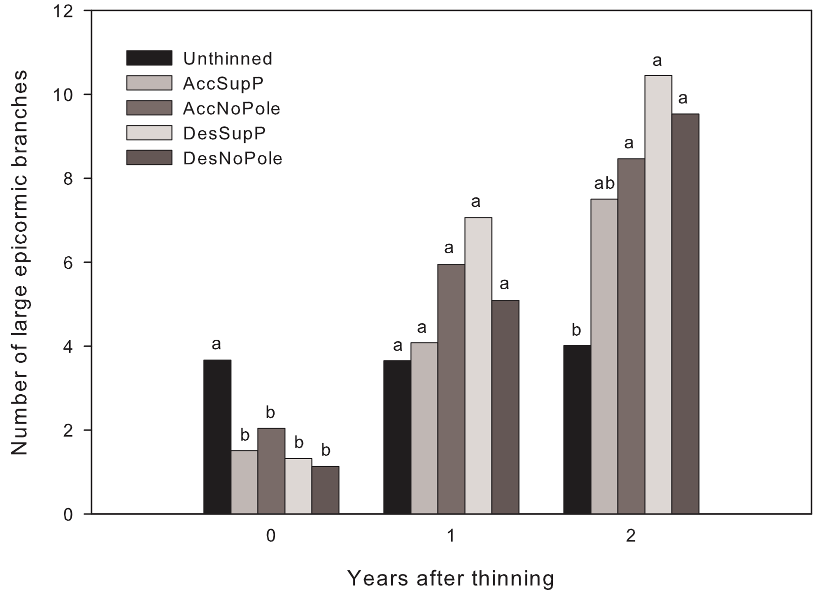

Figure 3—Number of large epicormic branches on the butt logs of residual water oak trees immediately after treatment and at the end of the first and second years following application of five thinning treatments in a 35-year-old water oak plantation in Louisiana. See table 1 for an explanation of treatment descriptors. Bars within a year followed by the same letter are not significantly different at the 0.05 level of probability.

The number of large epicormic branches on the butt logs of water oaks in the unthinned control plots remained fairly stable (at about four branches) during the two years after thinning (fig. 3). However, there were notable increases in the number of large epicormic branches on the butt logs of residual water oaks in all thinned plots during the same two year period. By the end of the second year after thinning, residual water oaks in all four thinning prescriptions, except AccSupP, had significantly more large epicormic branches than did water oaks in the unthinned control. The number of large epicormic branches on residual water oaks in the AccSupP prescription did not differ significantly from the number of large epicormic branches on water oaks in either the unthinned control or the other three thinning prescriptions.

To evaluate the response of the larger water oak trees in the plantation to the five thinning treatments, we partitioned the epicormic branch data by tree size class—sawtimber versus poletimber (fig. 4). Among sawtimber-sized trees at the end of the second year after thinning, there were more than twice as many large epicormic branches on the butt logs of residual water oaks in the thinned plots, relative to water oaks in the unthinned control plots. These differences in response between the thinned plots and the unthinned control plots were statistically significant. However, the number of large epicormic branches on residual sawtimber-sized water oaks did not differ significantly among the four thinning prescriptions.

There appears to be a separation in the level of the epicormic branch response between the two "Acceptable" prescriptions and the two "Desirable" prescriptions (fig. 4). Residual sawtimber-sized water oaks in the two "Acceptable" prescriptions averaged 7.3 to 7.9 large epicormic branches on the butt log at the end of the second year after thinning, whereas residual sawtimber-sized water oaks in the two "Desirable" prescriptions averaged 9.0 to 9.3 branches, although this separation was not statistically significant. Residual superior poletimber stock trees in the DesSupP prescription had significantly more large epicormic branches on the butt log than did residual superior poletimber stock trees in the AccSupP prescription (fig. 4).

The apparent separation in the level of the epicormic branch response between the two "Acceptable" prescriptions and the two "Desirable" prescriptions becomes more distinct when we limit the analysis to crop trees—preferred growing stock and desirable growing stock trees only (fig. 5). The two "Desirable" prescriptions resulted in significantly more large epicormic branches on the butt logs of high-value preferred and desirable growing stock trees at the end of the second year after thinning than did the two "Acceptable" prescriptions. Depending on the specific thinning prescriptions compared, the average increase ranged from 2.2 to 3.2 branches.

The two "Desirable" prescriptions apparently had a greater effect on the production of epicormic branches than did the two "Acceptable" prescriptions, especially among high-value preferred and desirable growing stock trees. The separation in the level of epicormic branch response between the "Acceptable" and the "Desirable" prescriptions most likely is due to differences in residual stand density after application of these two types of thinning prescriptions, as discussed in the previous section. Residual basal areas in the two "Acceptable" prescriptions were 47 and 54 square feet per acre, indicative of a marginally understocked, but still manageable, stand. Residual basal areas in the two

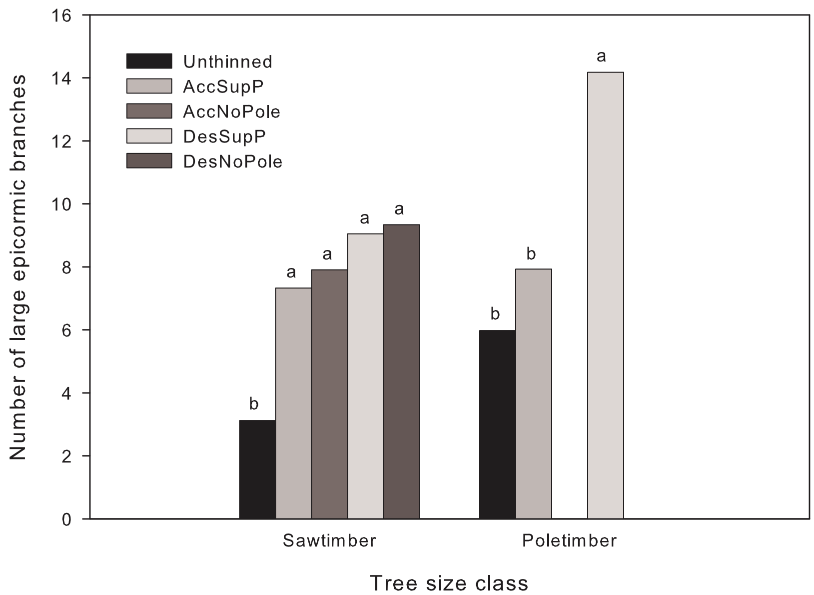

Figure 4—Number of large epicormic branches on the butt logs of residual water oak trees, by tree size class, at the end of the second year following application of five thinning treatments in a 35-year-old water oak plantation in Louisiana. See table 1 for an explanation of treatment descriptors. Bars within a tree size class followed by the same letter are not significantly different at the 0.05 level of probability.

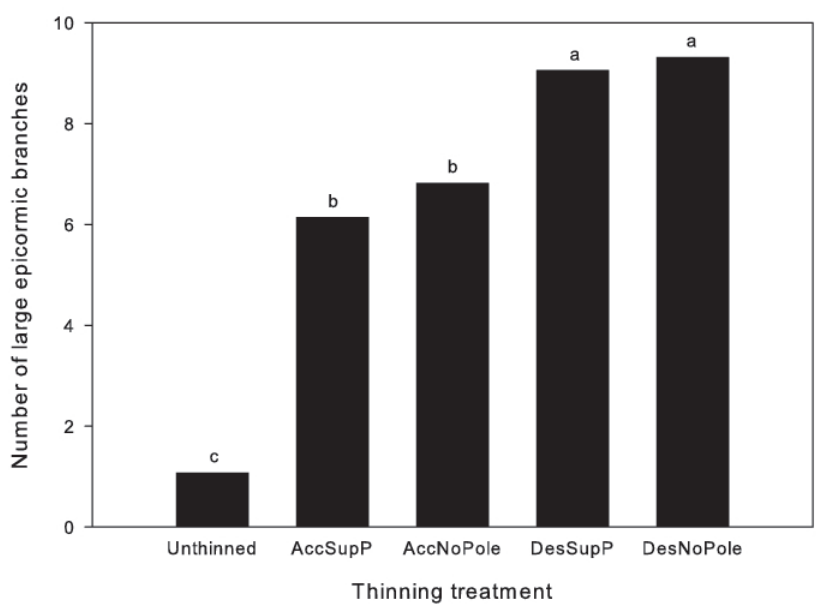

Figure 5—Number of large epicormic branches on the butt logs of residual water oak trees, in the preferred growing stock and desirable growing stock tree classes only, at the end of the second year following application of five thinning treatments in a 35-year-old water oak plantation in Louisiana. See table 1 for an explanation of treatment descriptors. Bars followed by the same letter are not significantly different at the 0.05 level of probability.

"Desirable" prescriptions were 30 and 33 square feet per acre, indicative of a severely understocked stand in which residual trees are essentially open-grown.

The DesSupP and DesNoPole prescriptions removed too many trees, reduced stand densities to unacceptable levels, and, consequently, stimulated the production of new epicormic branches on the butt logs of residual trees. On the other hand, retention of the acceptable growing stock trees in the AccSupP and AccNoPole prescriptions maintained residual stand density at a more favorable level, reduced the amount of sunlight to the boles of residual trees, and minimized the production of new epicormic branches, especially on the butt logs of high-value preferred and desirable growing stock trees. In stands of medium initial quality, such as this 35-year-old water oak plantation, acceptable growing stock trees should be retained after thinning to serve as "shelter" trees for the more valuable preferred and desirable growing stock trees.

Regardless of the manner in which we partitioned the data to examine the epicormic branch response by various stand components, the bottom line is that the number of large epicormic branches produced on the butt logs of residual trees in this water oak plantation was greater than that generally associated with well-designed thinnings in natural, mixed-species stands of bottomland hardwoods (Meadows and Goelz 2002, Meadows and Skojac 2006). The number of branches produced following thinning in our study was, at best, only marginally acceptable for the goal of high-quality sawtimber production.

Three factors likely contributed to the production of numerous epicormic branches along the boles of the residual trees in this study. First, water oak is highly susceptible to the production of epicormic branches (Meadows 1995). Second, bottomland red oaks do not compete well with other oaks when grown in pure stands (Aust and others 1985), such as this water oak plantation, whereas they are generally able to gain a competitive advantage over other species when grown in even-aged, natural stands of mixed species composition (Clatterbuck and Hodges 1988). As a result of long-term oak versus oak competition, individual trees in this water oak plantation may have been more stressed than was visibly apparent at the time of thinning. Hardwood trees, especially most bottomland red oaks, growing under stressful conditions exhibit an increased tendency to produce epicormic branches following thinning (Meadows and Goelz 2001). Third, all of our thinning prescriptions produced residual stand densities well below the acceptable range for natural stands proposed by Meadows and Goelz (2002) and by Meadows and Skojac (2006). The combination of a highly susceptible species subjected to the intense stress of oak versus oak competition in this single-species plantation and the low residual densities to which the plantation was thinned produced adverse effects on bole quality, in the form of numerous epicormic branches along the boles of residual trees.

CONCLUSION

Even though all four thinning prescriptions had negative impacts on bole quality of residual trees, the early results presented here indicate that the Acceptable With Superior Poletimber thinning prescription produced the best combination of (1) acceptable residual stand density, (2) improved diameter growth, and (3) least adverse effect from the production of epicormic branches in this previously unmanaged, mid-rotation water oak plantation.

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MORPHOLOGICAL AND PHYSIOLOGICAL RESPONSES OF HARDWOOD TREES TO PLANTATION THINNING

Martin-Michel Gauthier and Douglass F. Jacobs[1]

Abstract—A mixed hardwood plantation in Indiana was selected as a pilot study to investigate physiological and morphological responses of northern red oak (*Quercus rubra* L.), white oak (*Q. alba* L.), and black walnut (*Juglans nigra* L.) to thinning. Trends from the first growing season after harvest suggest average daily soil water content and soil temperature were higher in thinned plots when compared to control plots. All three species showed higher net photosynthesis rates in thinned plots. Increased production of photosynthate allowed trees in thinned plots to allocate more resources toward secondary growth as shown by increased diameter growth. Thinning, however, did not appear to increase soil nutrients, leaf water potential, crown surface area or height growth in a single growing season. Results suggest some variables responded to thinning during the first growing season after harvest, while others did not. Morphological parameters will be monitored to determine if current trends continue in subsequent years.

INTRODUCTION

In the Central Hardwood Forest Region of the United States, pure and mixed hardwood plantations have great economic potential. Intermediate silvicultural treatments such as thinnings have long been recognized as techniques to increase tree growth and quality. The increase in diameter growth and improvement in residual tree quality following thinning has been well documented in the past (Cutter and others 1991, Dale 1968, Hilt 1979, Oliver and Larson 1996). Changes occurring at the physiological level, however, are not well documented for deciduous forest tree species. To improve our ability to better predict responses after thinning and adjust silvicultural guidelines accordingly, there is a need to understand the nature and magnitude of hardwood tree responses to a change in available growing space. A pilot study was established in a mixed hardwood plantation to investigate morphological and physiological responses of northern red oak (*Quercus rubra* L.), white oak (*Q. alba* L.), and black walnut (*Juglans nigra* L.) during the first growing season after thinning. When compared to unthinned control plots, we hypothesized that thinned plots would have (1) increased soil water content, soil temperature, and soil nutrients; (2) trees with higher photosynthesis rates and leaf water potential; and (3) trees with higher mean diameter growth, height growth, and crown expansion.

METHODS

Study Area and Treatments

The mixed hardwood plantation is located in Colburn, IN (40°23' N, 86°56' W). The plantation was established in 1994 and appears to be at the beginning of the stem exclusion stage (Oliver and Larson 1996). Mean annual temperature, precipitation, and frost-free intervals are 10.1 °C, 937 mm, and 233 days, respectively (National Climatic Data Center 2004). Kalamazoo loam is the dominant soil type on this former agricultural land; it is characterized by deep, well drained soils formed in loamy outwash overlying sand or loamy sand (National Resources Conservation Service 2007). Northern red oak, white oak, black walnut, and black cherry (*Prunus serotina* Ehrh.) bareroot seedlings (1+0) were planted at 2.4 by 2.4 m spacing by the Indiana Department of Natural Resources. Mean (± SE) diameter at breast height (d.b.h.) for each species was 5.3 ± 0.3, 7.0 ± 0.2, 7.7 ± 0.3, and 11.9 ± 0.6 cm, respectively. Mean height for each species was 6.0 ± 0.2, 6.1 ± 0.1, 6.7 ± 0.2, and 8.7 ± 0.4 m. All species had 80 percent or more survival except for northern red oak with 56 percent. Four 400 m^2 square plots were established in a randomized complete block design. Two plots were thinned to 55 percent residual density while dormant based on guidelines for black walnut (Anonymous 1981) and oak (Gingrich 1971) and two plots were left as control plots. Each plot consisted of 8 by 8 rows (20 by 20 m) for a potential total of 64 trees. Black cherry had poor form, likely due to heavy browse damage; it was removed first (eight trees per plot). Smaller and less vigorous trees of all other species were cut until the required amount of trees per plot (34) was attained. On average, the number of trees cut per plot for northern red oak, white oak, and black walnut was 2, 3, and 7, respectively. The number of trees left for each species was 7, 13, and 14. The remaining ten trees were lost to mortality. One buffer row was established around each plot and treated in the same manner as the plot. A minimum of 20 m was left between each plot. Slash and debris from thinned trees were moved outside plot boundaries. Plots were mowed twice per month to reduce confounding effects from understory vegetation.

Soil and Tree Measurements

A soil moisture probe and temperature probe (Decagon Devices Inc., Pullman, WA) connected to a data logger (Onset Computer Corp., Bourne, MA) were installed in each plot for the months of July and August. Each probe was located within a 2-m radius of one tree selected for physiological measurements. The soil moisture probe measured volumetric water content (m^3/m^3) for the first 20 cm of the soil horizon; the temperature probe measured to a depth of 5 cm. Three soil samples were collected in the upper 10 cm of the mineral horizon of each plot in April, June, and August to determine N, P, and K content based on methods for the North Central Region (Brown 1998). Samples were sent to a professional laboratory for analysis (A&L Great Lakes Laboratories Inc., Fort Wayne, IN). Net photosynthesis rates (*A*) were measured twice per month between 9:00

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and 10:30 from June to August. Two trees of each species were sampled in each plot for a total of 24 trees. Two fully expanded leaves from the middle of the canopy (about 3 m in height) were chosen from each measurement tree. Photosynthesis measurements were conducted with a portable photosynthesis system (LI-6400, Li-Cor Biosciences Inc., Lincoln, NE). A light level of 1,200 μmol/m²/s¹ and ambient [CO_2] of 380 μmol/ mol¹ were specified in the chamber of the infrared gas exchange analyzer. Predawn and midday leaf water potential (Ψ) were measured on half of the trees selected for photosynthesis measurements using a pressure chamber (PMS Instruments Co., Albany, OR). Height, d.b.h., and crown surface area were measured prior to thinning and at the end of the first growing season. Crown surface area was calculated based on formulas from Brack (1999).

Statistical Analysis

Statistical analysis for this pilot study was descriptive in nature. The planting pattern was not uniform and did not allow us to establish more than four plots. With the plot as the experimental unit, sample size (n=4) did not allow for t-test or analysis of variance. For the first objective, data were plotted and descriptive statistics were used to compare means and associated variation. For the second and third objectives, data from trees measured over the course of the growing season were used to generate box charts for each measured variable. This approach identified general trends in the data.

RESULTS

Mean daily soil water content was 0.19 ± 0.01 m^3/m^3 in thinned plots compared to 0.13 ± 0.01 m^3/m^3 in control plots. Mean daily soil temperature was 26.3 ± 0.3 °C in thinned plots compared to 22.9 ± 0.2 °C in control plots (fig. 1). Thinning did not measurably alter soil nutrient content within a single growing season following the thinning treatment. Box charts showed a trend toward higher net photosynthesis rates for trees in thinned plots for all three species (fig. 2). No clear trend was detected in predawn or midday leaf water potential measurements. A tendency toward higher diameter growth was found in thinned plots for all three species (fig. 3), but height growth appeared to be higher in control plots for all species as well. Thinning did not alter crown surface area.

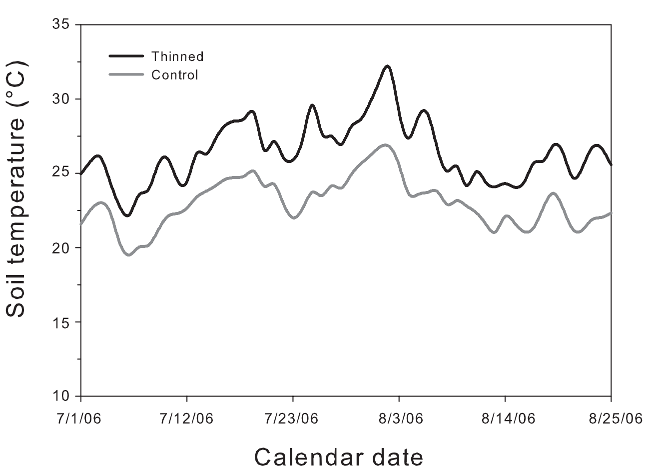

Figure 1—Mean daily soil temperature in thinned and control plots during the first growing season after thinning.

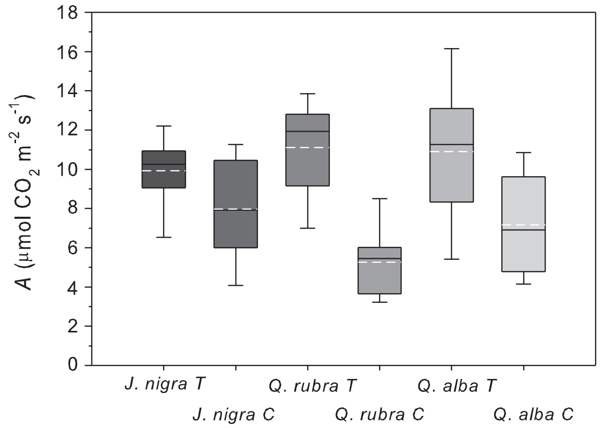

Figure 2—Box chart of net photosynthesis rates for each species and treatment (T = thinned, C = control) for the first growing season after thinning. Mean is shown by dashed line and median is shown by solid line, boxes represent one standard deviation from the mean, and whisker caps indicate 5th and 95th percentiles.

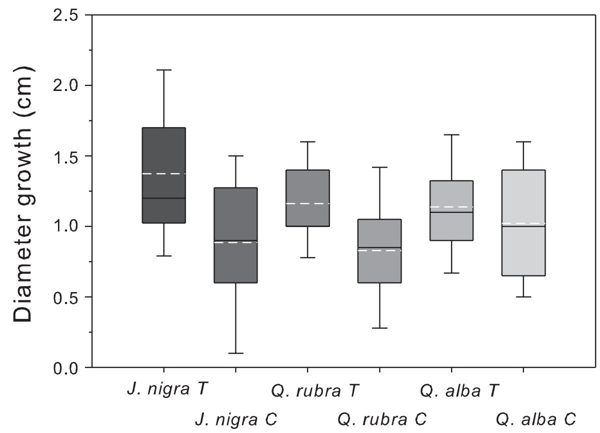

Figure 3—Box chart of diameter growth for each species and treatment (T = thinned, C = control) one growing season after thinning. Mean is shown by dashed line and median is shown by solid line, boxes represent one standard deviation from the mean, and whisker caps indicate 5th and 95th percentiles.

DISCUSSION

Results suggest some parameters responded immediately to thinning while others did not. Thinning increased soil water content, soil temperature, and net photosynthesis rates of residual trees of all three species. This was expected and is in agreement with previous thinning studies of conifers (Aussenac 2000, Sala and others 2005, Skov and others 2004). Diameter growth is mainly determined by environmental conditions from the current growing season, and increased production of photosynthate allowed trees in thinned plots to allocate more resources toward secondary growth. Height growth, however, is a function of the conditions from the previous growing season, at least for determinate growth species like black walnut. This may help explain the lack of response in height and crown surface area. Many oak species such as northern red oak can have additional flushes of shoot growth if conditions are favorable, but morphological responses to thinning may be delayed by two years or more with this species (Ward 2002).

Other variables also failed to respond to thinning. More time appears necessary to detect any changes in soil processes and nutrient content resulting from the increase in water content and temperature, albeit our sampling scheme may not have been extensive enough to detect actual trends. First and second year responses to thinning in mature sessile oak (*Q. petraea* (Matt.) Liebl.) stands in France showed increased predawn leaf water potential due to higher extractable water in the soil (Bréda and others 1995). Annual precipitation in 2006 was much higher than the long-term average in Indiana; this could have significantly lowered any potential water stress that might have occurred during a normal year. The lack of response of morphological parameters such as height and crown surface area may change over the next few growing seasons. They will be monitored to determine if current trends continue. This pilot study served as a template for additional experiments aimed at determining how plantation-grown hardwood trees respond to thinning in terms of photosynthetic activity and leaf morphology.

ACKNOWLEDGMENTS

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THE SYLVIEW GRAPHICAL INTERFACE TO THE SYLVAN STAND STRUCTURE MODEL WITH EXAMPLES FROM SOUTHERN BOTTOMLAND HARDWOOD FORESTS

David R. Larsen and Ian Scott[1]

Abstract—In the field of forestry, the output of forest growth models provide a wealth of detailed information that can often be difficult to analyze and perceive due to presentation either as plain text summary tables or static stand visualizations. This paper describes the design and implementation of a cross-platform computer application for dynamic and interactive forest stand visualization, titled Sylview (Scott 2006). Sylview allows users to visualize many aspects of forest stands from overall stand makeup to wood quality characteristics of individual trees. From these visualizations the user can infer the effects of different stand management practices. A primary focus in the design of the Sylview is usability. Sylview features a simple, interactive interface and intuitive visualizations focusing on legibility. As part of the development of Sylview a new data structure was designed for the efficient retrieval of required data, which will also be applied to future growth model development.

INTRODUCTION

Forest growth models and in particular the Sylvan Stand Structure model produces an estimate of individual tree growth and outputs the result as a tree list in an ASCII file format. These tree lists are very difficult for people to read and interpret the changes that occur to individual trees. In this paper we are describing a graphical user interface that displays the information in the output tree list in a form that is very easy for people to observe and comprehend.

The Sylvan Stand Structure model (Larsen 1991, 1991a, 1994) was developed in the early 1990s to allow forester to predict the development of specific stand with unique characteristics. The model is spatially explicit, uses crown size to determine tree growth in different dimensions. This model unlike other forest growth models that depend on region average data uses the data collected from specific plots, along with generalized stand dynamics principles that allow the model to be used in many regions of the world with many different species. The Sylvan Stand Structure model has been calibrated to data from the states of WA, MO, AR, MS, and TN. The model has also been calibrated to data from the countries of Finland, Austria, Italy, and Columbia. It has been used with both hardwoods and conifers arranged in both plantations and natural stands.

Because of the difficulty of understanding tree list data several visualization tools have been used over the years to help user understand the model output. The Sylvan Display program (Davison 1995) and the Stand Visualization System (SVS) (McGaughey 1997) are two visualization tools that can be used with Sylvan. However, the data stored in the Sylvan data file is much richer than the previous tools can display. Additionally, the previous software was written in the mid-1990s and program tools have improved considerably in the last 10 years. It was decided to develop a new visualization called Sylview (Scott 2006)

Sylview has benefited from the work of other in the development of forest stand visualization. Two significant efforts include the Sylvan display program (Davison 1995), and Stand Visualization system (McGaughey 1997). Both of these models read tree list data and display the results as 2- and 3-dimensional figures as well as 2-dimensional graphs.

Mark Davison developed a visualization project, Sylvan Display program, as a M.S. thesis in 1995. This project had several goals including a 2- and 3-dimensional graphical interface to the Sylvan data and the need to compile across computer platforms, Linux, Windows and Macintosh. Mark substantially completed these tasks although the software programming tools at the time were cumbersome and difficult to use. Figure 1 is a screenshot of the Sylvan Display program interface. One nice feature of this program is that all controls are on the display window. There are not menu structures to navigate to change options of window behavior.

The second visualization tool that we also viewed in the development of our software is Stand Visualization System (SVS) (McGaughey 1997) (fig. 2). This software has many improvements on the Sylvan Display program. The ability to view tree list data and display data in 2- and 3-dimensions, and graph the data are improved. Two issues that are not part of SVS are that it is a Windows only program and many of the display control features are several levels down in a menu system.

VISUALIZATION AND USER INTERFACE DESIGN

Given the review of these programs, we came up with a list of what the Sylview program should do for the user.

- Present a plot of trees in map and profile view
- View the individual tree characteristics through time.
- Visualize the internal wood characteristics of individual trees through time.

Other considerations that we included in the design: 1) the program must run on multiple platforms (Windows, Mac, Linux/Unix), and 2) the program must rely on vector-based 2D graphics for abstracted, easy to understand views and

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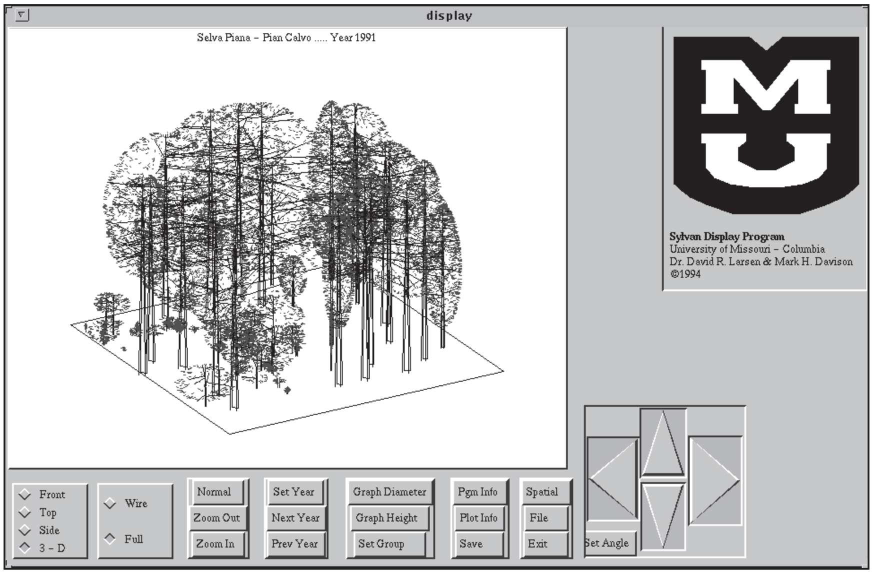

Figure 1—Screenshot of the Sylvan Display program (Davison, 1995).

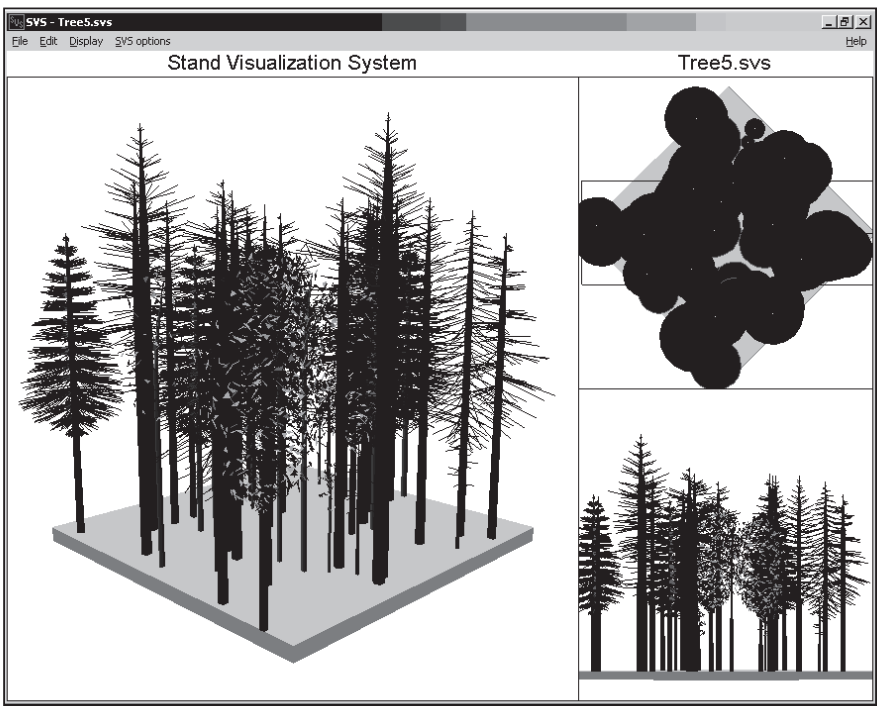

Figure 2—Screenshot of Stand Visualization System (SVS) (McGaughey, 1997).

smooth screen and print display. To accomplish this we used C++ computer language with the Qt cross-platform application framework. Additionally, we used the Sylvan C++ Library, allowing a common file input and output as well as the access to the growth model.

In designing the interface we followed two principles, 1) the principle of least surprise, the user should never be surprised at the results of his or her actions and 2) the functioning of the program should be intuitively obvious, this means objects function as the user expects. For example if a user clicks on an object (a tree) other windows about that tree or more information about the object should be presented.

The Sylvan stand structure model runs on basic tree measurements. They include diameter at breast height, total height, crown width, crown length, and crown base (fig. 3). These measurements along with the tree location are the basis of all the visualizations in Sylview. A profile view such as figure 5 is simply two polygons the crown and the stem. The stem is drawn using taper equations; currently two are available. First is the taper equations based on Walter and Hann 1986 (fig. 4). These are natural looking, made up of two equations, one for above breast height and one for below breast height. These equations output, diameter as a specified height, and are sensitive to the crown length.

Because tree taper in the stem taper equations is influenced by tree crown and we have the crown history in the stand simulation process, we can produce a predicted tree stem profile. This stem profile graph was inspired by a graph presented in Assmann, 1970 (fig. 5). In figure 5, the diagram on the left is the original graph illustrating the branch knot

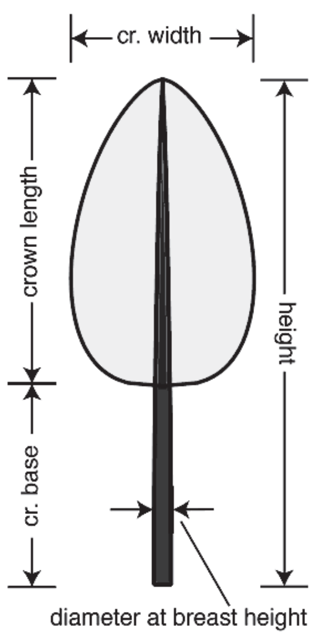

Figure 3—Diagram illustrating the two polygons used to draw a tree. The tree dimensions are labeled on the image.

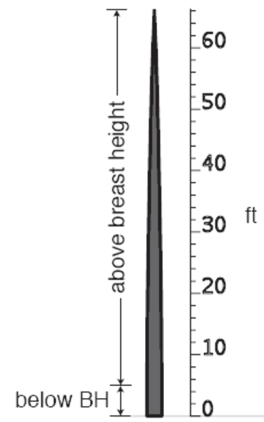

Figure 4—Diagram showing the tree stem drawn with the stem taper equations.

zones within a spruce tree. On the right is the branch zone profile produced for one tree using the stem taper and crown history as predicted by the Sylvan Stand Structure model. In this illustration the upper portion is the green knot zone, the next portion is mixed knot zone, then the black knot zone, and the bottom portion is the clear wood zone.

APPLICATIONS

There are many uses for software of this type. We would like to describe several of the potential uses. This software

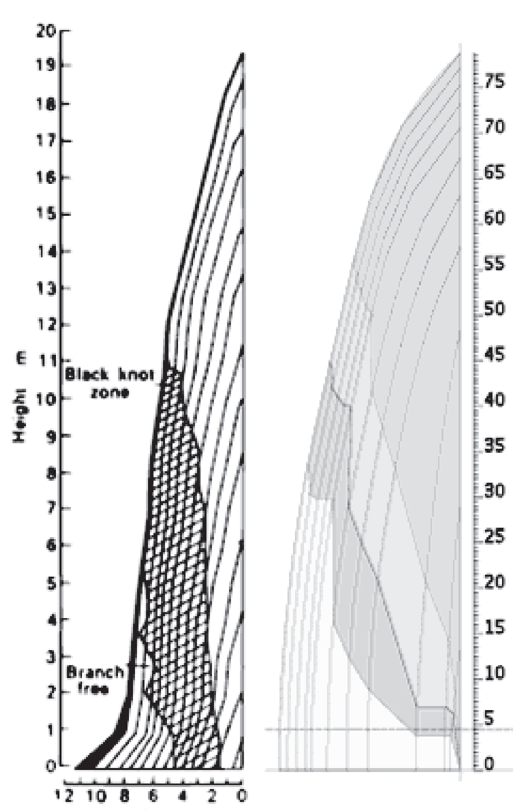

Figure 5—Diagram to illustrate the probable internal structure of the tree stem as modeled by the growth model.

is very useful for the analysis of consequences of stand management decision. The growth model is growing a single plot with the specific spatial patterns that you observe in the map and profile views (fig. 6). Given the local density around a specific tree, the model predicts the change in crown size as that tree grows and its consequences on components of wood quality. By growing high density stands, the trees will have low taper stems and small breast height diameters. Growing trees and wider spacing the trees will have higher taper rates but larger breast height diameters. Trees growing in a hole in the canopy grow at the local density, not the stand average density. These capabilities allow the user to experiment with stand management and learn how that management can change the character of the residual trees.

We have also used the software to step through repeat measurement tree data looking for measurement errors. Finding errors in repeat measurement data is quite difficult. The visualizations allow a quick and very intuitive interpretation of the data.

We have used the Sylview visualization to detect error in the underlying growth model. Many errors are very subtle and very difficult to perceive. The use of visualization tools allows one to quickly detect problems and focus the debugging efforts on the apparent problems.

DISCUSSION

One of the nicest features of the Sylview model is the ease of use. Once the data are loaded in to the model and the simulation runs have been made, the access to the information about the trees in the plot is excellent. There are interactive map and profiles views with tree labeling (fig. 6). Once a tree is selected an interactive stem profile, crown profile and stem cross-section are available (fig. 7). Alternatives for the selected tree and local area leaf area profile are available to help you understand the driving forces in changing crown dimensions. Also traditional stand, stock and over time tables are available as well as Gingrich and Renieke stocking diagrams (Gingrich 1967, Reineke 1937) (fig. 8).

There is a need for additional development; we plan to add a log sort table which will take the stem profile cut them into logs and tabulate them by size and quality. Additionally we have been working on providing more information on branch size and density with in the simulated logs. These factors are all related to the change in crown dimensions over time, which is a component of a stand that the forester can control.

The Sylvan program and the data viewed in Sylview, while looking like a growth and yield model is different than the typical growth and yield models. This model uses several stand dynamics principles, and statistical relationship from the subject stand to define the tree parameters. These are designed to allow some flexibility not available in other

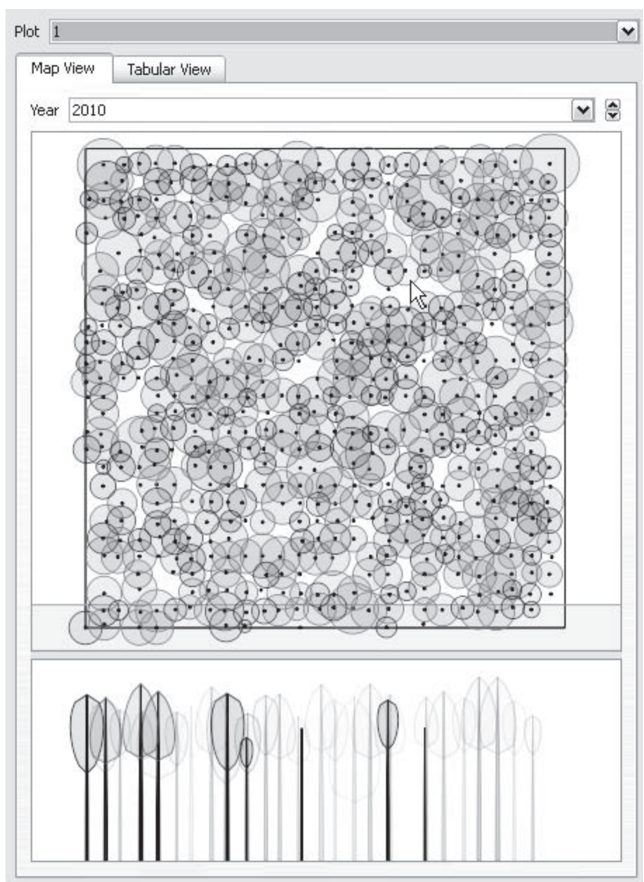

Figure 6— Map and profile views of the simulated tree data.

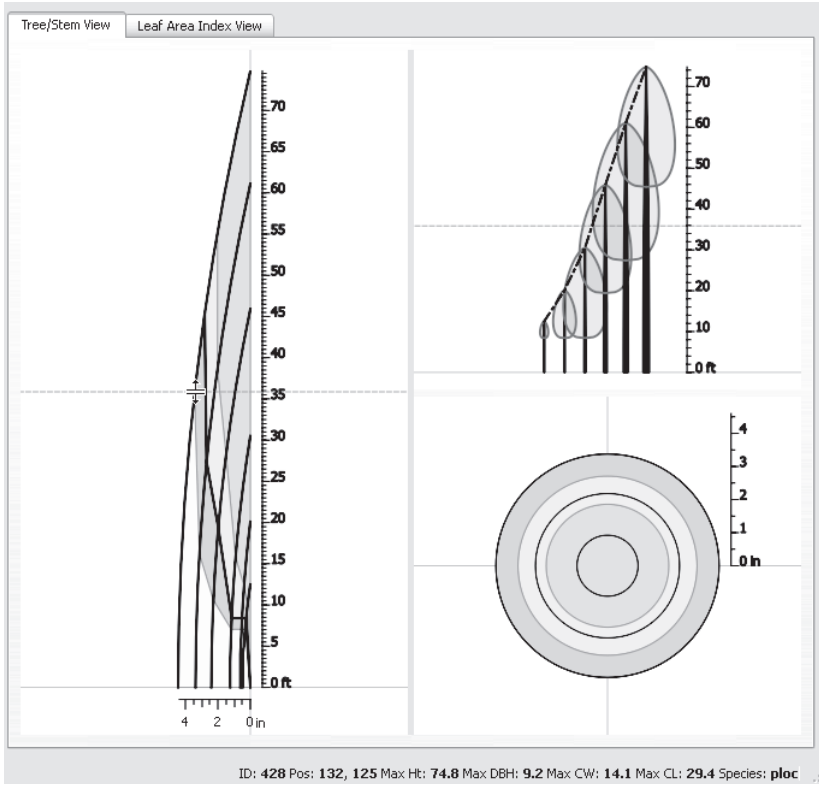

Figure 7—Individual tree information for a single selected tree. These plots include internal tree structure, crown change profile and stem cross-section (Note rings are 5-year increments).

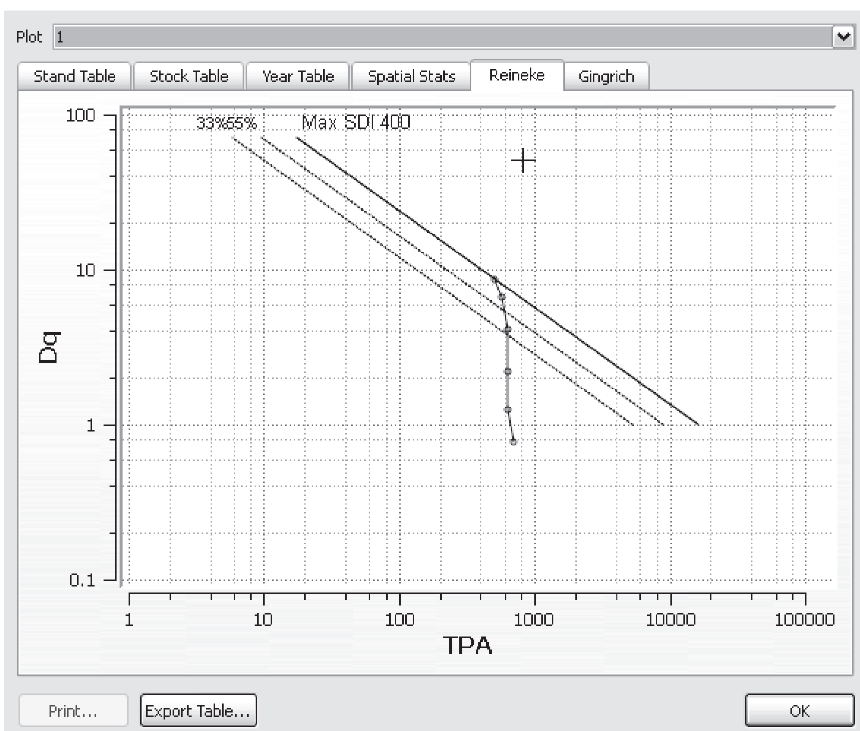

Figure 8—Reineke density management diagram with the simulated data plotted.

growth models. This also requires that the user to check the realism of the results. Research continues on methods to allow flexibility with sufficient safeguards so that the user can use the model with a high degree of confidence.

CONCLUSION

Several goals were met with this project: 1) view tree growth in graphical and text-based forms; 2) inspect the internal wood structure; 3) produce standard forestry statistical tables; and 4) export graphic for reports. This project completed the major goals of producing a user friendly graphical interface that provides easy access to that complex relationship found in the tree simulation data over time. Like all project there are areas for extension and improvement but the current work provides a big step forward in access to the modeled tree data.

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Hardwood Natural Regeneration

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OAK REGENERATION FOLLOWING COMPLETE AND PARTIAL HARVESTING IN THE MISSISSIPPI BLUFF HILLS: PRELIMINARY RESULTS

Brian Roy Lockhart, Rodney J. Wishard, Andrew W. Ezell, John D. Hodges, and W. Norman Davis[1]

Abstract—The Bluff Hills subregion encompasses about 4.5 million acres along the eastern side of the Mississippi Valley Loess Plains province, primarily in MS and TN. Soils are silt loams and are considered some of the most productive hardwood sites in the United States. Efforts to regenerate these forests to oak (*Quercus* spp.) has met with limited success. Due to these difficulties in regenerating oak, we initiated a study to test several regeneration methods. Three treatments included clearcut harvesting, partial harvesting using a combination of even-aged and uneven-aged techniques, and partial harvesting followed by herbicide-injection of less-desirable species. We conducted pre-harvest measurements, followed by first (stocking only), fifth, and eleventh year post-harvest measurements on three sites in Warren County, MS. Results after 11 years showed that clearcut plots were dominated by yellow-poplar (*Liriodendron tulipifera* L.), despite the continued presence of oak reproduction. Partial harvesting increased oak reproduction stocking, but after 11 years this reproduction was competing with a shade-tolerant midstory canopy. Partial harvesting combined with midstory competition control greatly increased oak reproduction stocking, but also increased yellow-poplar reproduction. These results indicate that different approaches, including timing of treatments, are needed to regenerate oak successfully in the Bluff Hills.

INTRODUCTION

The Bluff Hills, commonly referred to as Brown Loam Bluffs (Hodges 1995), constitute a sub-region of the Mississippi Valley Loess Plains province (Bailey 1980). They extend from Baton Rouge, LA, to Cairo, IL, adjacent the east side of the Lower Mississippi Alluvial Valley (Hodges 1995), encompassing about 4.5 million acres (Johnson 1991). Soils are of aeolian origin and highly productive. These soils are also erosive; therefore, the Bluff Hills are characterized as deeply gullied with narrow ridges and steep slopes due to past agricultural land use (Hodges 1995).

Johnson (1958, 1991) indicated the Bluff Hills are one of the most productive hardwood areas in the United States. Site index, base age 50 years, can be > 100 for several oak species on lower slopes (Broadfoot 1976). This sub-region is considered a disjunct remnant of the Appalachian mixed mesophytic forest (Braun 1950), and contains a high diversity of plant species (Johnson and Little 1967, Caplenor 1968, Miller and Neiswender 1987a, 1987b). Forests, especially oak-(*Quercus* spp.) dominated forests, became established on former agricultural land following abandonment in the early to mid-1900s. Interest in managing these forests has increased as the stands have matured. Unfortunately, many of the oak regeneration problems that have been encountered in other productive hardwood forests (Loftis and McGee 1993, Johnson and others 2002) also occur in the Bluff Hills. Therefore, we initiated a study to determine the effects that different harvesting practices, along with midstory canopy control, have on the density of oak reproduction.

MATERIALS AND METHODS

Three study sites (Gooch-Dixon Tract, Logue Tract, and Swift Tract) were located in the Bluff Hills on Anderson-Tully Company lands in Warren County, MS. The average annual temperature in Warren County is 65.5 °F with a low of 47.2 °F in January and a high of 81.7 °F in July. Rainfall averages 58 in per year (Mississippi State Climate Office, http://www.msstate.edu/dept/geosciences/climate/normals.html). Soils are Memphis, Natchez, and Loring silt loams (USDA 1964). They are considered deep, well drained, and productive. Site index, base age 50 years, is estimated to be 100 to 120 feet for cherrybark oak (*Q. pagoda* Raf.). Past stand history includes agricultural abandonment in the early 1900s followed by forest succession. Periodic light harvests have been conducted since the mid 1900s.

Sixty sample plots were systematically located in each study site in 1989 (180 plots total). These circular plots were 0.01 acre. This plot size was chosen to use Johnson's (1980) evaluation technique for determining oak reproduction stocking. Sample plots were located along transects 264 feet (4 chains) apart with individual plots 132 feet (2 chains) along each transect. Exceptions were made if sample plots were likely to be destroyed in skid trials, log dumps, or creek beds. Landform position was noted for each sample plot: ridge, slope, or bottom. All stems were measured prior to harvest in height (inches) or diameter at breast height (d.b.h., inches) if d.b.h. was > 0.5 inch. Post-treatment measurements involved stem counts by size classes. Pretreatment basal area was determined using a 10-factor prism and summed for sample plot basal area per acre. Pretreatment tree composition was determined using importance values (sum of relative frequency, relative density and relative dominance; Krebs 1985).

Hart and others (1995) modification of Johnson's (1980) evaluation technique was used to determine oak reproduction stocking on each sample plot. Points are assigned to stems based on height or d.b.h. (see Hart and others (1995) for

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more information about size classes). If points total 12 or more, then the sample plot is considered stocked with desirable reproduction (Johnson 1980). If 60 percent of the sample plots in a stand are stocked, then the stand is considered adequately stocked for a clearcut harvest to successfully regenerate the stand to oak (Johnson and Deen 1993).

Each study site (90 acres) was harvested in the late summer/early fall 1989. Three harvest treatments were conducted on about 1/3 of each study site. These treatments were: (1) a commercial clearcut followed by a herbicide injection using Tordon 101R® of all remaining stems ≥ 1-inch d.b.h.; (2) a partial harvest following Anderson-Tully Company's marking guidelines involving a tree classification system (see Putnam and others 1960 and Lockhart and others 2005 for examples); and (3) a similar partial harvest followed by herbicide injection of all remaining less-desirable stems ≥ 1 inch d.b.h. Sample plot remeasurements were conducted 1 (1990; oak stems only), 6 (1995), and 11 (2000) years following harvesting. We analyzed data using each study site as a replicate in a randomized complete block design, although the clearcut treatment was designated as the middle treatment in each study site to facilitate harvesting. The remaining treatments were randomized. Seedling densities from each sample plot were pooled by treatment within each study site, then converted to per acre values. We analyzed the data using log transformations. Percent data were analyzed using arcsine transformations. Repeated measures analysis was conducted using PROC GLM (SAS 1985), with significance determined at $p \leq 0.05$ and means separation using Duncan's Multiple Range Test.

RESULTS AND DISCUSSION

A total of 44 tree species > 4.5 inches d.b.h. were identified across all study sites prior to treatment (Wishard 1991). Dominant species included cherrybark oak, sweetgum (*Liquidambar styraciflua* L.), yellow-poplar (*Liriodendron tulipifera* L.), white oak (*Q. alba* L.), and American beech (*Fagus grandifolia* Ehrh.) (table 1). The ten most important species comprised 79 percent of total importance values (table 1). Oaks comprised 43 percent of total importance values. Preharvest basal area averaged 106 square feet per acre with no difference between designated treatments (p=0.4212, fig. 1). Following harvesting, the partial harvest treatments had greater residual basal area than the clearcut treatment (p=0.0153, fig. 1). These basal area values were obtained prior to the injection treatment.

Total reproduction density of all species prior to harvest was 7,070 seedlings per acre. No difference existed between designated treatments in 1989 (p=0.0975, fig. 2). Six years after treatment reproduction density had declined 41 percent across all treatments (p=0.0049 for the time and treatment interaction). A higher density was found in the clearcut treatment compared to the partial harvest treatments (p=0.0126, fig. 2). Eleven years after treatment, reproduction density had declined another nine percent compared to pre-harvest density. No differences were found between treatments (p=0.6086).

Table 1—Importance values (sum of relative density, relative dominance, and relative frequency) for trees > 5.5 in d.b.h. across three study sites in Warren County, MS

Species	Importance value
Cherrybark oak (*Quercus pagoda* Raf.)	69.6
Sweetgum (*Liquidambar styraciflua* L.)	36.0
Yellow-poplar (*Liriodendron tulipifera* L.)	25.2
White oak (*Q. alba* L.)	21.2
American beech (*Fagus grandifolia* Ehrh.)	20.5
Shumard oak (*Q. shumardii* Buckl.)	16.2
Bitternut hickory (*Carya cordiformis* (Wangenh.) K. Koch)	14.5
Water oak (*Q. nigra* L.)	13.0
White ash (*Fraxinus americana* L.)	12.2
Sassafras (*Sassafras albidum* (Nutt.) Nees)	7.2

Among oak reproduction, 1,281 seedlings per acre were tallied prior to treatment, or 18 percent of total reproduction. A difference was found between designated treatments with the partial harvest/inject treatment having 41 percent less oak reproduction compared to the other treatments (p=0.0431, fig. 3). Six years after harvesting, oak reproduction density had declined 65 percent (p=0.0001 for time effect) to 443 stems per acre (p=0.9597). A 15 percent increase in oak reproduction was noted 11 years after treatment (p=0.8470, fig. 3).

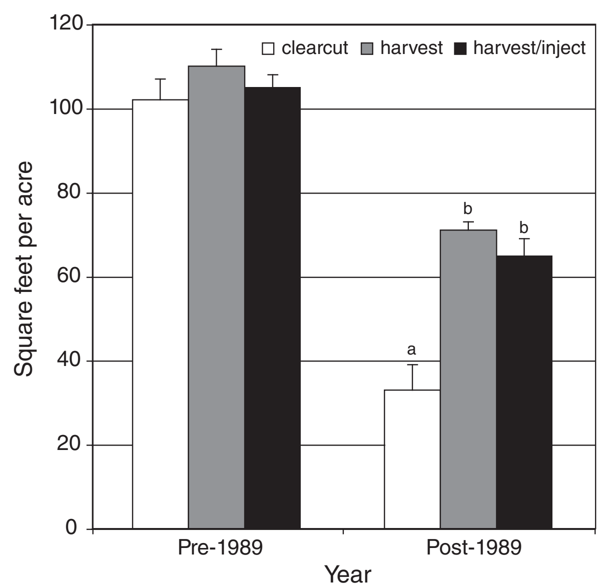

Figure 1—Pre- and post-harvest basal area per acre by treatment in the Bluff Hills, Warren County, MS. Bars represent one standard error. Columns followed by different letters within a year are significantly different at $p \leq 0.05$.

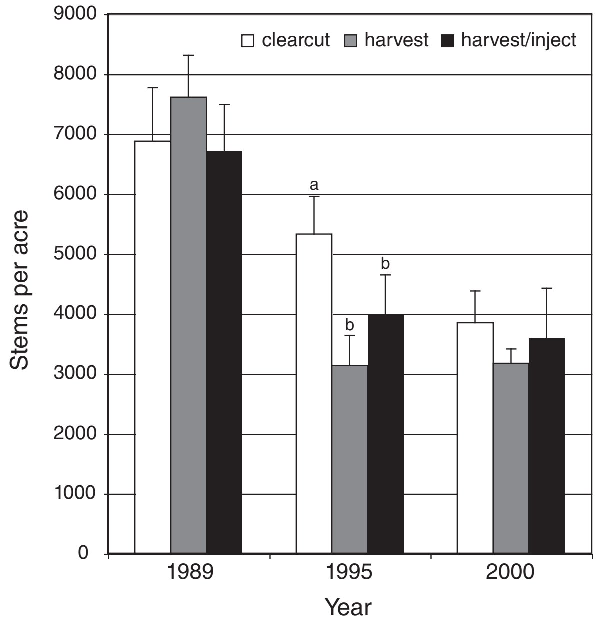

Figure 2—Hardwood reproduction per acre by treatment in the Bluff Hills, Warren County, MS. Bars represent one standard error. Columns followed by different letters within a year are significantly different at p ≤ 0.05.

No differences were found in oak reproduction within each size class between treatments in 1989, 1995, or 2000, due primarily to large variation between treatment means. Therefore, oak reproduction density was pooled among treatments. A majority of oak reproduction existed in the < 1 foot height class (fig. 4, table 2). Eighty-six percent of all oak reproduction was < 1 foot in height in 1989. This percentage decreased to 21 percent by 1995, but increased to 53 percent following the 2000 growing season (p=0.0001 for time effect; table 2). The 269 seedlings per acre < 1 foot in height in 2000 were distributed among the treatments as follows: 8, 54, and 38 percent among the clearcut, partial harvest, and partial harvest/inject treatments, respectively (p=0.0705, fig. 4). Observations in the field indicated that the 1999 growing season produced a bumper acorn crop, resulting in the recruitment of new seedlings into the < 1 foot height class. Higher percentages among the partial harvest/inject and partial harvest treatments was expected, because these treatments maintained a mature oak canopy that provided acorns.

In general, oak density declined with increasing size class and time (table 2). An exception occurred with reproduction > 3 feet tall but < 0.5 inch d.b.h. in 1995 and the largest size class in 2000 (table 2). The increase in oak reproduction in these size classes reflects ingrowth from seedlings in the smaller size classes. The 257 stems per acre in 1995 was also the result of the two larger size classes tallied together (table 2). Noteworthy is the largest percentage of stems for these two densities were found in the clearcuts. Fifty-two percent of the stems >3 feet tall but < 0.5 inch d.b.h. in 1995 were found in the clearcut treatment compared to 29 and 19 percent in the partial harvest/inject and partial harvest treatments, respectively. Likewise, 71 percent of the stems in the largest size class in 2000 were found in the clearcut treatment.

While a larger percentage of oak stems in the 0.5 to 5.5 inch d.b.h. class in 2000 appeared in the clearcut treatment, many of these stems were suppressed. We made an assessment in each clearcut plot as to which tree would likely dominate the plot over time. In most cases, the choice of species was clear. Yellow-poplar dominated in the clearcuts, i.e., it was the dominant species in 81 percent of the plots (table 3). Yellow-poplar was a major component of the stands prior to treatment, although stem numbers were considerably less than were the oaks (table 1). Previous experience with

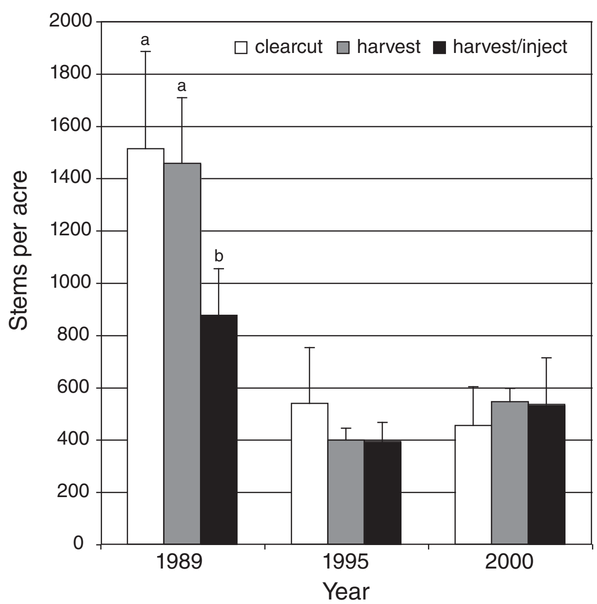

Figure 3—Oak reproduction per acre by treatment in the Bluff Hills, Warren County, MS. Bars represent one standard error. Columns followed by different letters within a year are significantly different at p ≤ 0.05.

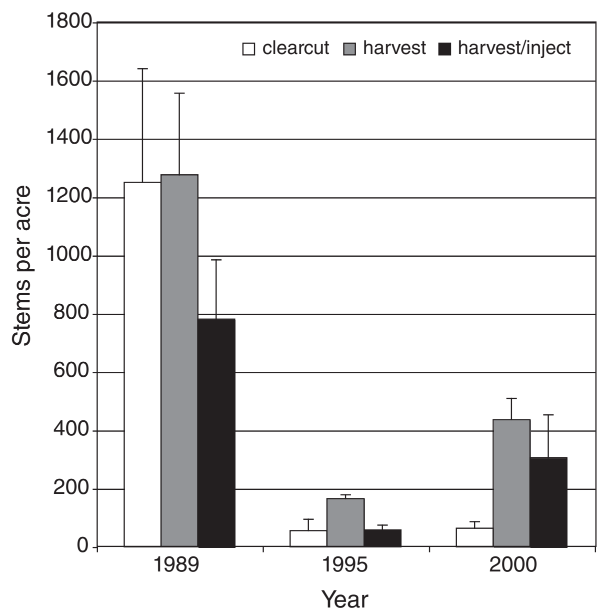

Figure 4—Oak reproduction per acre < 1 foot in height by treatment in the Bluff Hills, Warren County, MS. Bars represent one standard error.

Table 2–Mean oak reproduction density (stems per acre) by size class for three measurement periods across three study sites in Warren County, MS

Size class	1989	1995	2000	p-value for time effect
< 1 foot	1,102 (87)	93 (22)	269 (50)	0.0001
1 to 3 feet	120 (9)	93 (22)	66 (13)	0.0845
> 3 feet, < 0.5 in d.b.h.	49 (4)	257 (56)	47 (9)	0.0001
0.5 to 5.5 in d.b.h.	10 (1)	---	131 (27)	0.0009
Total	1,281 (18)	443 (11)	511 (15)	0.0001

Numbers in parentheses represent one standard error of the mean.

yellow-poplar in the southern Appalachians indicates that a few trees in the overstory canopy will provide enough seed to dominate the regeneration pool following clearcut harvest, because its seed remain viable in the seed bank for eight years, and it has the ability to grow rapidly in conditions of high light (Clark and Boyce 1964, Beck and Hooper 1986). Yellow-poplar densities in 1995 were 940, 549, and 117 stems per acre in the clearcut, partial harvest/inject, and partial harvest treatments, respectively—a gradient of decreasing sunlight (fig. 5). Yellow-poplar densities were still > 500 stems per acre after 11 years in the clearcut treatments (fig. 5). Oaks and elms (*Ulmus* spp.) each dominated seven percent of the plots in the clearcuts while white ash (*Fraxinus americana* L.) and sweetgum combined dominated the remaining five percent (table 3). The oak-dominated plots were located on ridge sites. These sites have lower site index compared to slopes and bottoms due to greater erosion, lower soil moisture holding capacity, and greater disturbance from logging equipment.

Using Hart and others (1995) modification of Johnson's (1980) reproduction evaluation technique, 25 percent of the plots in the present study were stocked with oak reproduction prior to harvesting. 41 percent of the clearcut plots were adequately stocked, which is 19 percent less than the recommended 60 percent before a clearcut harvest should be conducted (Johnson and Deen 1993). Adequate stocking increased to 57 percent in the clearcut plots one year following harvesting and remained around 55 percent throughout the study period (fig. 6). While the number of stocked plots remained relatively high, much of this reproduction was suppressed by yellow-poplar.

Table 3—Dominant tree on clearcut plots 11 years after harvesting across three study sites in Warren County, MS

Species	No. plots	Percent	Ridge	Slope	Bottom
Yellow-poplar	35	81.4	5	29	1
Oaks	3	7.0	3	0	0
American elm	3	7.0	0	2	1
White ash	1	2.3	0	1	0
Sweetgum	1	2.3	1	0	0

Partial harvesting nearly doubled the number of stocked plots one year following treatment (25 percent in 1988 to 49 percent in 1990). Stocking remained near 50 percent six years after treatment then fell to 33 percent 11 years after treatment (fig. 6). Stocking was greatly increased by partial harvesting and injection of the shade-tolerant midstory. Initial stocking was only 8 percent, but increased to 38 percent one year after treatment. Stocking then increased to 45 percent six years after treatment before falling to 36 percent in 2000 (fig. 6).

Previous work indicates that disturbance is necessary to sustain oak in southern mixed-species upland hardwood forests (Johnson and others 2002, Loftis 2004). Examples include the Bluff Hills (Goelz and Meadows 1995), Ozarks (Spetich and Graney 2004), Appalachians (Loftis 1985, 1990), and the Cumberland Plateau (Schweitzer 2004). Unfortunately, disturbance alone does not guarantee successful oak regeneration. The degree of disturbance, source of oak reproduction, and the influence of competing

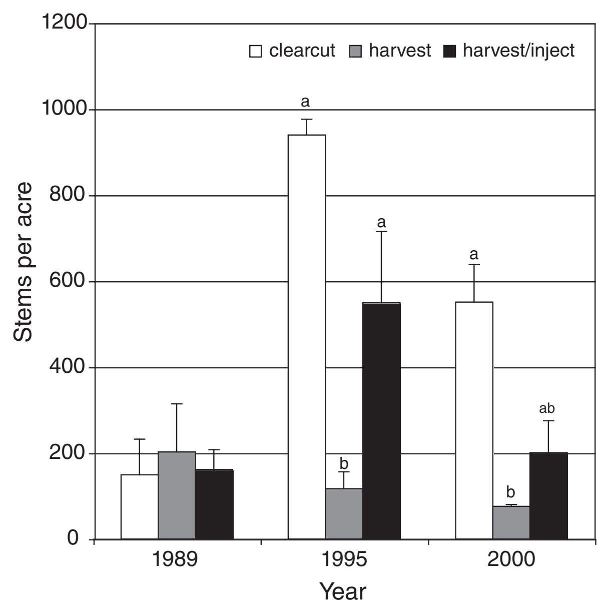

Figure 5—Yellow-poplar reproduction per acre by treatment in the Bluff Hills, Warren County, MS. Bars represent one standard error. Columns followed by different letters within a year are significantly different at p ≤ 0.05.

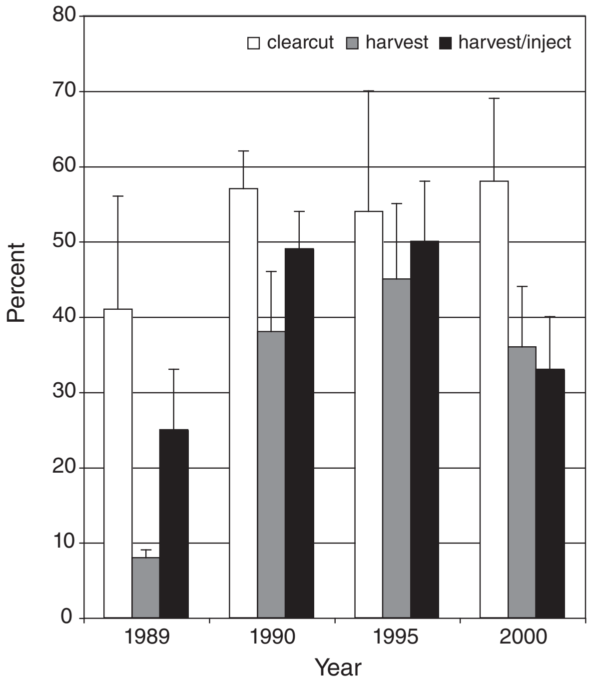

Figure 6—Percent of oak reproduction stocked 0.01-acre plots by treatment in the Bluff Hills, Warren County, MS. Bars represent one standard error.

species are also important factors in successful oak regeneration (Loftis 2004).

In our study, a heavy disturbance, such as clearcutting, in a mixed-species stand with a yellow-poplar component resulted in yellow-poplar dominated stands 11 years after harvesting. The oak composition in these stands after 11 years was significantly reduced relative to their dominance in the previous stand. Similar results were found following clearcutting in southern Appalachian hardwood stands (Beck and Hooper 1986). In the Bluff Hills, yellow-poplar is considered a desirable timber species; therefore, if the management objective includes yellow-poplar and the species is present in the stand, then a heavy disturbance is all that is needed to sustain or even increase the yellow-poplar component. Oak reproduction stocking in the clearcut areas was still relatively high at 58 percent (fig. 6), but much of this reproduction was suppressed by yellow-poplar. Release treatments have been proposed as one way to increase oak seedling or sapling competitiveness when overtopped by competing species, but these treatments have had mixed results (Trimble 1973, 1974, Smith 1983).

The partial harvesting in this study, conducted using Anderson-Tully Company guidelines, does not follow classical regeneration methods. It can probably best be described as an irregular shelterwood with components of single-tree and group selection combined with low and crown thinning. About 1/3 of the basal area was removed during partial harvesting operations. Trees with quality boles and relatively large crowns were maintained in the overstory. Past observations have indicated that desirable reproduction, especially oak, was inconsistent following these partial harvests. Oak reproduction stocking improved following the partial harvest, but still did not reach the minimum 60 percent recommendation before a final removal harvest (Johnson and Deen 1993). Further, the proportion of oak stems compared to total reproduction remained constant, 19 percent prior to harvest and 17 percent 11 years after harvest, but about 1/2 of this reproduction was seedlings < 1 foot in height. We observed in both the partial harvest and partial harvest/inject treatments the presence of many one year old seedlings indicating a recent bumper acorn crop. Many of these seedlings will perish without a follow-up treatment to increase light levels (Crow 1988, 1992). Yellow-poplar reproduction density decreased from 203 stems per acre prior to harvest to 76 stems per acre 11 years after harvest. The shade-tolerant midstory canopy, which was left intact, had a positive effect in reducing the yellow-poplar reproduction density, but concurrently was keeping the oak reproduction from growing into larger height classes.

Partial harvesting combined with injection of midstory stems was designed to further increase light levels reaching advance oak reproduction and the forest floor by removing less-desirable, shade-tolerant species. This treatment is similar to one proposed by Loftis (1990), except partial harvesting was conducted in the overstory canopy. Loftis (1990) proposed a shelterwood method for regenerating red oak in the southern Appalachians that involved reducing basal area by about one-third, but the trees were removed from below using herbicides, leaving the main canopy intact. Loftis (1990) stated this treatment would prevent yellow-poplar from becoming established and growing prior to the final removal cut. In addition, the shade-tolerant midstory would be removed, increasing the light levels reaching advance oak reproduction and may allow for the establishment of new oak reproduction if the treatment coincided with a bumper acorn crop. Lockhart and others (2000) showed that removal of the midstory canopy alone would increase light levels reaching the forest floor from 5 to 10 percent to 40 percent. Loftis (1990) further stated that a final removal harvest could be conducted about 10 years after the initial herbicide treatment.

Oak reproduction stocking apparently improved following the partial harvest treatment. Stocking increased 375 percent one year following treatment, and reached 45 percent stocking six years after treatment before declining to 33 percent stocking 11 years after treatment (fig. 6). Yellow-poplar density also increased following treatment from 162 stems per acre prior to treatment to 549 stems per acre six years after treatment. Yellow-poplar density declined to 201 stems per acre 11 years after treatment ($p=0.0004$ for time effect). Based on Loftis's (1990) findings, the partial harvesting in the overstory, while benefiting oak reproduction, also allowed for the establishment and growth of excessive yellow-poplar. We further observed that a new shade-tolerant midstory canopy was developing 11 years after treatment. These stems came primarily from advance reproduction that was too small to inject at the time of midstory competition control in 1989.

Little research has been conducted regarding silvicultural practices in the Bluff Hills sub-region. This is surprising given the rich soils and high quality hardwoods that can be grown there (Fickle 2001). Much of this land was cleared for agriculture during the late 1800s and early 1900s, before being abandoned due to boll weevil infestations (Fickle 2001).

Forests have succeeded abandoned agricultural land and pastures and, as these forests mature, landowners need information on management options. This is particularly true for regenerating desirable species such as the oaks. The Bluff Hills probably can be considered similar to the higher quality sites found in the southern Appalachians. Results from hardwood research in this region, such as the shelterwood method (Loftis 1990) and prescribed fire (Barnes and Van Lear 1998, Brose and others 1999), may have use in the Bluff Hills, but research is needed to confirm the applicability of these recommendations to the Bluff Hills.

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PRE- AND POST-CLEARCUT TREE SPECIES DISTRIBUTION IN TWO PHYSIOGRAPHIC REGIONS OF THE SHAWNEE NATIONAL FOREST, ILLINOIS

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Abstract—Seventy-four upland oak stands distributed across the Shawnee National Forest, Illinois were inventoried 15 to 26 years after clearcutting and harvest records examined to determine the effect of physiographic province on the distribution of oak and associated tree species before and after clearcutting. Oak represented 62 percent of harvest volume in the Shawnee Hills versus 51 percent in the Ozark Plateau. The latter is characterized by high site quality resulting from the deposition of wind blown loess soils originating from the adjacent Mississippi River floodplain. Oak proportion based on stem density was significantly less in post-clearcut stands in both physiographic provinces but a pre-harvest trend toward relatively higher values in the Shawnee Hills (21 percent) versus the Ozark Plateau (11 percent) persisted. The increased dominance of yellow-poplar across the Shawnee Hills could have important management implications if this species persists.

INTRODUCTION

The oak-hickory (*Quercus*/*Carya*) forest is the primary forest type in the Central Hardwood Forest (CHF), covering 127 million acres (Hicks 1998). The oak/hickory forest type is important to the CHF because oak (*Quercus* sp.) trees are an important primary producer (Ostfeld and others 1996), supporting a diverse and productive ecosystem. Acorns are used by over 180 birds and mammals across the United States (Rogers 1990), and are a highly preferred food source for rodents, squirrels, birds, chipmunks, wild turkey, and white-tail deer.

The pre-settlement forests in southern IL varied widely in composition depending on topography, slope position and physiographic region (Fralish and others 1991). Two major upland forest types are recognized for southern IL: the mesic oak-hickory forest of the Shawnee Hills and the mixed hardwood forest of the Ozark Plateau (Leitner and Jackson 1981). The Shawnee Hills extends across southern IL from east to west and the Ozark Plateau is located on the western border of southern Illinois along the Mississippi River floodplain.

The mesic oak-hickory forest of the Shawnee Hills consisted of white oak (43.6 percent), black oak (19.6 percent), northern red oak (2.2 percent), and hickory species (6.8 percent) which combined for 72 percent importance (Leitner and Jackson 1981). The Mixed Hardwood Forest occurred in the western portion of the Shawnee Hills and within the Ozark Plateau. Site quality on broad ridgetops and ravines in the Ozark Plateau was increased by the deposition of loess soils from the adjacent Mississippi River floodplain (Fralish 1976). Greater soil depth, moisture availability and competition relative to the Shawnee hills located to the east. High site quality increased the development of the Mixed Hardwood Forest in the Ozark Plateau. Importance percentages for white and black oak were 24.7 and 9.5 percent, respectively (Leitner and Jackson 1981). The deep loess soils also supported typically mesophytic species, especially American beech [*Fagus grandifolia* (22.1 percent)], sweetgum [*Liquidambar styraciflua* (8.3 percent)], and yellow-poplar [*Liriodendron tulipifera* (6.9 percent)] (Leitner and Jackson 1981). The mixed hardwood community consistently dominated the Ozark Plateau landscape.

Clearcutting is the removal of the entire stand in one entry, including all merchantable and unmerchantable timber 2 inches in diameter and greater (Smith 1986). Clearcutting is intended to create the conditions necessary for rapid growth of moderately shade tolerant and shade intolerant species, and for the development of an even-aged stand. Historically, clearcutting had proven to be a successful technique in halting succession and promoting oak regeneration, as well as that of other shade intolerant hardwood species (Bey 1964). More recently, land managers have struggled to maintain the oak/hickory forest type with this silvicultural technique (Lorimer 1993). The suppression of fire has left the understory of oak/hickory stands stocked with shade tolerant mesophytic species and an abundant yellow-poplar seed supply (Beck and Della–Bianca 1981). These individuals out compete oak seedlings for dominance upon release from overstory suppression.

Between 1980 and 1990, the United States Forest Service conducted 160 clearcuts throughout the Shawnee National Forest, with the stated objectives of regenerating the stands to valuable hardwood species, such as red and white oak, white ash, and yellow-poplar. The objectives of this study were to identify past and present distribution of oak and other common tree species across two physiographic regions and to evaluate the effectiveness of clearcutting in achieving management goals.

METHODS

The 74 stands used in this study were chosen randomly from 160 total stands that were clearcut by the Shawnee National Forest between 1980 and 1990. These stands were located in the Ozark Plateau and Shawnee Hills physiographic regions and were representative of the full range of landscape positions found therein. Transects were

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systematically located on topographic maps to represent a wide range of topographic and site quality variation within each stand. Inventory plots were placed at equal distances along the transect line. Selected stands were assigned four to six inventory plots (depending on size) which were located on photocopied maps prior to inventorying sites.

A total of 343 inventory plots were installed during summers 2005 to 2006. Data were collected at each plot using the Common Stand Exam (CSE) protocols (Common Stand Exam Users Guide 2003). Overstory data were collected using a 10 basal area factor variable radius plot. All tallied trees were measured for diameter at breast height (d.b.h.), total height, crown class, and crown ratio, and identified to species. Sales folders maintained by the Shawnee National Forest were available for 57 of the stands. These reported stumpage quantities by species groups in thousand board feet units. Species groups most often used by Forest Service personnel who created these records were white oak, red/black oak, mixed hardwoods, and yellow-poplar. These data were used to determine past species composition.

Present and past oak proportions were analyzed as a function of physiographic region. Present, but not past, oak proportions were transformed with a square root transformation to satisfy the assumptions of ANOVA. This analysis sought to determine the effects of longitude and associated site quality on oak density. Because of their location relative to one another, physiographic region acted as a proxy for longitude.

Species that represented more than 6.5 percent of the total density for all trees tallied were used for individual analysis (table 1). These included *Quercus alba, Quercus rubra, Quercus velutina, Acer saccharum, Prunus serotina,* and *Liriodendron tulipifera*. Northern red oak and white oak had densities less than 6.5 percent of the total density, but were included in the individual analysis because they were considered keystone species (Bond 1994). All hickory species were grouped into a *Carya* category. These species include *Carya ovata, Carya glabra, Carya illinoensis, Carya cordiformis,* and *Carya tomentosa*.

Table 1—Relative density of oak and associated species (6.5 percent or greater) across 74 stands 15-26 years following clearcutting in the Shawnee National Forest

Species	Relative stem density (*percent*)
Yellow-poplar (*Liriodendron tulipifera*)	13.9
Sugar maple (*Acer saccharum*)	11.8
Black cherry (*Prunus serotina*)	6.9
Black oak (*Quercus velutina*)	6.9
Sassafras (*Sassafras albidum*)	6.8
White oak (*Quercus alba*)	5.4
Northern red oak (*Quercus rubra*)	1.8

RESULTS

Past oak percentage as measured by harvest was greater in the Shawnee Hills (62 percent) than the Ozark Plateau (51 percent) (f=4.09, df=1, p=0.0481). 15-26 years following clearcutting, oak proportions as measured by stem density was lower in both physiographic provinces than pre-harvest volumes. The regions did not differ significantly from one another by this measure (f=2.65, df=1, p=0.1094) but pre-harvest trends remained with oak density higher in the Shawnee Hills (21 percent) versus the Ozarks (11 percent).

Yellow-poplar represents 14 percent of the total tree density and 29 percent of basal area across the 74 post-clearcut stands (table 1). In contrast, all oak species combined comprised 15 percent total basal area. Pre-settlement records indicate that yellow-poplar was limited to lower slope positions on north aspects and on terraces, where it reached 17 percent importance (Fralish 1991). Sales folders indicated that yellow-poplar comprised 15 percent of the volume in pre-harvest stands, of which 89 percent came from the Ozark Plateau.

Differences in species distribution were noted between the physiographic provinces following clearcutting 43, 57 and 78 percent of the respective density northern red oak, black oak, and white oak in the Shawnee Hills. Hickory had 43 percent of its density in the Shawnee Hills. Mesophytic distribution is also variable across physiographic regions. Following clearcutting, 37, 45, and 72 percent of sugar maple, yellow-poplar, and black cherry density were in the Shawnee Hills.

DISCUSSION

Pre-harvest oak proportion was lower in the Ozark Plateau versus the less productive Shawnee Hills. This is consistent with previous observations in this region (Fralish 1976). Oak species have shown a decrease in density from pre-harvest to mid-rotation age. This finding supports the work of others who have observed a decrease in oak density across a range of site qualities in eastern oak forests (Beck and Hooper 1986, Elliot and others 1997, Gould and others 2005, Jenkins and Parker 1998).

The decrease in oak species within these stands appears to be more prevalent in the Ozark Plateau than in the Shawnee Hills. Similar results were found in PA where third generation oak stands regenerated in equal proportions in the Ridge and Valley and Blue Ridge provinces, areas where oak dominated second generation forests. In contrast, third generation oak dominated stands were totally absent in the Appalachian Plateaus, where the previous oak forest was in transition with the mesophytic Allegheny hardwood forest type (Gould and others 2005), a situation similar to the mixed hardwoods and productive sites of the Ozark Plateau.

Species distribution across the landscape appears to be more strongly driven by life history characteristics and growth patterns. For example, yellow-poplar was a small component of presettlement and second growth forests, existing primarily on the lower north and terrace slope positions (Fralish 1991). Pre-harvest data showed yellow-poplar was mostly found on high quality sites in the Ozark Plateau at densities far smaller than oak and hickory species. Today, yellow-poplar is widely distributed across landscape positions in both physiographic provinces, even where it was historically rare or absent (Fralish 1991). The relatively high proportion of sugar maple in the Ozark Plateau is expected considering the mesic site conditions associated with this region. The prevalence of yellow-poplar and black cherry in the relatively dry Shawnee Hills is noteworthy. Continued persistence of these species at the expense of oaks would represent a significant change in species composition toward mesophytes in this relatively dry region. Further monitoring will be needed to determine whether the present dominance of meosphytes in Ozark Plateau and Shawnee Hills stands originating from clearcutting portends a lasting compositional change. If so, intermediate silvicultural treatments may be considered to satisfy current management objectives focused on maintaining oak dominance.

CONCLUSION

The occurrence of third generation oak species in even-aged upland hardwood stands is primarily an effect of site quality and life history characteristics. Oak in upland clear cut stands approaching mid-rotation in the Shawnee National Forest has decreased from 55 percent total pre-clearcut volume to 16 percent post clearcut density. The increasing similarity of forest composition between the Ozark Plateau and Shawnee Hills suggests that different silvicultural strategies should be specified within these regions if maintaining pre-harvest composition is a priority. Management activities implemented at this stage of development could help influence future stand composition, increase d.b.h. growth and crown development of desirable species, and increase mast production for wildlife habitat and future regeneration sources. Questions remain regarding the survivability of yellow-poplar and black cherry on drought-prone, low quality sites and of northern red oak on high quality sites where competition is intense.

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EFFECTS OF PRE- AND POST-HARVEST SITE PREPARATION TREATMENTS ON NATURAL REGENERATION SUCCESS IN A MIXED HARDWOOD STAND AFTER 10 YEARS

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Abstract—Advance regeneration, sprouts and seeds are sources of reproduction in the regeneration of mixed hardwood stands following harvest. The control of undesirable, non-commercial, competing vegetation is a common technique in site preparation to promote the establishment and growth of desirable species. This study was designed to evaluate the effectiveness of pre- and post-harvest site preparation treatments in the regeneration of an upland hardwood stand near Oak Ridge, TN. Four site preparation treatments (pre- and post-harvest slashing, with and without herbicide stump treatment) and a control (no slashing or herbicide treatment) were implemented. Each set of five treatments was replicated six times. The regeneration harvest was conducted during the winter of 1996-1997. After ten growing seasons, there was little statistical difference in species composition between treatments. Even though many undesirable existing stems were controlled by the pre- and post-harvest site preparation treatments, the proliferation of light-seeded species, primarily yellow-poplar (*Liriodendron tulipifera*), red maple (*Acer rubrum*), black cherry (*Prunus serotina*), and Virginia pine (*Pinus virginiana*) overcompensated for the various site preparation treatments.

INTRODUCTION

Ensuring adequate regeneration of preferred species in mixed hardwood stands following a harvest is often a concern to forest managers. A myriad of different species with different site requirements and growth habits and varying sources of reproduction (seed, sprouts, advance regeneration) make prediction of regeneration complex and sometimes unreliable. Often competition from undesirable trees is too great for the commercially important species to overcome.

One means of encouraging growth of preferred, regenerating species is by limiting competing trees through site preparation either before or after the harvest operation. Slashing and/or the use of herbicide are two methods of site preparation. Little information is available to assess the relative effectiveness of these various site preparation alternatives. Loftis (1978, 1985) evaluated the effectiveness and costs associated with preharvest treatments on Appalachian hardwoods. The results suggest that after clearcutting, preharvest treatments reduce the number of stems of undesirable species and increase the proportion of desirable species in the stand. After ten years, stands that received preharvest treatments were well-stocked with single stems of desirable species.

Loftis (1978, 1985) only used a post-harvest treatment as a check on the effectiveness of the preharvest treatments. A herbicide application was only used with the preharvest operation; no herbicide was used in post-harvest treatments. Our study considers how a stand develops after a regeneration harvest when a variety of pre- and post-harvest site preparation treatments is applied.

OBJECTIVES

The purpose of this study was to evaluate the effect of pre- and post-harvest slashing and herbicide stump treatment of non-commercial stems on species composition following a silvicultural clearcut. Ten-year results are presented. Hodges and others (2002) reported two-year results on species composition and the costs associated with the pre- and post-harvesting treatments.

METHODS

The study was located on a 17-acre watershed at the University of Tennessee Forest Resources Research and Education Center near Oak Ridge, TN. Elevations in the south-facing drainage range from 970 to 1100 feet above sea level. Site index (base age of 50 years) for upland oaks ranged from 65 to 75 feet (Olson 1959). The harvested sawtimber stand was comprised primarily of oaks (*Quercus* spp.) (69 percent) by volume, yellow-poplar (*Liriodendron tulipifera*) (14 percent), miscellaneous hardwoods (10 percent), and pines (*Pinus* spp.) (6 percent).

Five treatments were implemented:

1. Preharvest slash only
2. Preharvest slash with herbicide stump treatment
3. Post-harvest slash only
4. Post-harvest slash and herbicide stump treatment
5. Control (no slashing or herbicide)

The five treatments were applied to 120 by 120 foot (0.33-acre) plots. This plot size was large enough to distinguish individual treatments from adjacent treatments while allowing for replications. Each set of five treatments was replicated six times for a total of 30 treatment plots. All treatment plots were located adjacent to each other.

Within each plot, four 1/100 acre subplots were established for sampling. Each subplot was located at a corner of a 60 by 60 foot square contained within the plot. The first subplot was established by running a line bisecting the northern corner of each plot for 42.5 feet. The remaining three subplots were

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positioned by running a 60-foot line parallel to the boundaries of the plot.

Plots were assigned to different replications by establishing groups of plots that were similar in terms of species composition, density, and location. A computer-generated design for incomplete blocks was used to assign treatments to plots.

The initial inventory before the harvest was conducted in June 1996. All trees above one foot in height were measured in the subplots during September 1996. Data were collected in several designated classes: 1 foot height classes to 4 feet tall, above 4 feet tall but less than 1.5 inches at diameter breast height (d.b.h., 4.5 feet), and by 1 inch diameter class above 1.5 inches. This methodology follows the regeneration prediction model designed and being tested by the USDA Forest Service, Southern Research Station, Bent Creek Experimental Forest near Asheville, NC.

Preharvest treatments were conducted on the designated plots during October 1996. The number of stems cut per plot was recorded as stems greater than or less than 1.5 inches d.b.h. Garlon 3A in a 50:50 mix with water and red dye was used on all non-commercial stumps, primarily red maple (*Acer rubrum*), blackgum (*Nyssa sylvatica*), sourwood (*Oxydendrum arboreum*), dogwood (*Cornus florida*), sweetgum (*Liquidambar styraciflua*), elms (*Ulmus* spp.), and beech (*Fagus grandiflora*). Herbicide was applied to the stump directly after cutting.

The timber harvest was conducted from February through April 1997. Approximately 118.9 million board feet of hardwood sawtimber, 7.0 million board feet of pine sawtimber, 29.2 cords of hardwood pulpwood and 9.0 cords of pine pulpwood were harvested.

Post-harvest treatments were conducted in August 1997 in the same manner as the preharvest treatments.

All subplots were measured after the second growing season (1999) and the results were reported by Hodges and others (2002). Measurements after ten growing seasons (2006) were collected during December 2006 and January 2007. Since the general canopy level after 10 years was 30 to 35 feet and the canopy was closed, data collected on each subplot were stem counts by species for all stems more than 4 feet in height. The most dominant tree on each subplot was identified and tallied by species and d.b.h.

RESULTS AND DISCUSSION

Few statistical differences were detected in the number of stems per acre by species and treatment (table 1). The only significant species component was the miscellaneous species category. Yellow-poplar comprised 43 to 50 percent of the total number of stems in each treatment, red maple 13 to 23 percent, black cherry 7 to 13 percent, oaks 5 to 7 percent and miscellaneous species 9 to 24 percent. Even though the site preparation treatments were conducted to control undesirable residuals and promote regeneration present, species that regenerate from light, wind-blown seed such as yellow-poplar, black cherry, red maple and Virginia pine had greater number of trees than oaks and hickories.

In addition, many of these species that regenerate readily from seed maintain seed viability on the forest floor for several years: yellow-poplar, four to seven years (Clark and Boyce 1964); black cherry, three or more years (Wendel 1977); and red maple, two or more years (Marquis 1975). Virginia pine seed remain viable for only one year. The viable seed accumulate in the forest floor after seed dissemination each year forming a seed bank ready to germinate when conditions are favorable, especially after a harvest. The wind-blown seed and the numerous seeds in the seed bank probably overburdened the regeneration present on the site prior to the harvest shifting the species composition toward these light-seeded species.

Red maple seed is different from other species that usually disseminate their seed in the fall. Red maple is one of the first species to flower in the spring. Its fruit ripens just before leaf development is complete. Seeds are dispersed in April through June, depending on location and climate. The seed are not dormant and do not require any pre-germination treatment. Seeds of red maple germinate within a few weeks of ripening and dispersal (Walters and Yawney 1990). Unlike most species that disseminate seed in the fall and germinate in the spring, red maple can actually regenerate and grow within the current growing season giving it an advantage or head start on other species, especially during spring and summer harvests. Red maple seed also stays viable in the forest floor for several years, increasing its regeneration advantages.

Preharvest treatments compared to post-harvest treatments had little effect on species composition (table 1). More than three times as many stems were treated in the preharvest plots than were recorded in the post-harvest plots (table 2). The harvesting operation resulted in many of the stems in the post-harvest plots being severed before the treatment was applied. The preharvest treatments were more costly to conduct than the post-harvest treatments (Hodges and others 2002). However, safety during slashing operations is also a concern. Slashing stands before harvest is much safer than slashing after the harvest when tree tops and other harvesting debris is on the ground. A balance between safety and cost should be considered during site preparation activities.

Effects of the herbicide treatment were varied. Miscellaneous species, primarily the midstory species of sourwood, blackgum and dogwood were impacted most during the preharvest slash and herbicide treatment (table 1). No definitive judgments can be made about the herbicide treatment and red maple. We observed that the herbicide treatment did kill many of the red maple residuals, but red maple was still prolific on the harvested area after 10 years, presumably from new and stored seed and some sprouting.

Table 1—Stems per acre by species and treatment (n = 24 subplots per treatment) after 10 years for the pre- and post-treatment site preparation regeneration study at the Forest Resources Research and Education Center, Oak Ridge, TN. Treatment differences by individual species were only found for the miscellaneous species category at the *alpha = 0.05* level (Tukey's procedure)

Species	Trmt #1[a]	Trmt #2	Trmt #3	Trmt #4	Trmt #5
Yellow-poplar	2733	2683	2383	2367	2770
Red maple	1073	1210	940	715	969
Black cherry	391	387	553	470	403
Oaks	295	265	382	340	424
Hickories[b]	75	104	79	129	91
Virginia pine	108	58	70	116	66
Miscellaneous species[c]	806 ab	480 b	775 ab	1285 a	1040 a
Total	5435	5187	5182	5422	5763

[a]Treatment #1 = Pre-harvest slash only
Treatment #2 = Pre-harvest slash and herbicide
Treatment #3 = Post-harvest slash only
Treatment #4 = Post-harvest slash and herbicide
Treatment #5 = Control (no slash or herbicide)
[b]Hickories (*Carya* spp.)
[c]Miscellaneous species includes beech, blackgum, dogwood, elms, hollies (*Ilex* spp.) sassafras (*Sassafras albidum*), sourwood, sweetgum, sumac (*Rhus* spp.), and white ash (*Fraxinus americana*)

Further evidence, beyond the number of stems, that yellow-poplar was the most common regenerating species is that 38 percent of the subplots had a yellow-poplar as the most dominant tree (table 3). Although oaks comprised the majority of the volume of the harvested stand, oaks represent a minority of the stems in the regenerating stand. Approximately, the same number of oaks is present in the regeneration after 2 years (Hodges and others 2002) as was observed after 10 years. Oaks were not affected by the treatments. However, 200 to 400 oaks per acre were present across treatments, with some dominating the subplots (table 3). Oaks will probably continue to be a component of the new stand, albeit at lower volumes and probably fewer trees compared to the harvested stand.

Table 2—Site preparation treatment applied (n = 24 subplots) for the pre- and post-treatment site preparation regeneration study at the Forest Resources Research and Education Center, Oak Ridge, TN

Treatment	Slashed	Herbicide
	(# of trees/acre)	
Pre-harvest	948	na[a]
Pre-harvest/ Herbicide	1383	607
Post-harvest	308	na
Post-harvest/ Herbicide	426	387

[a]na = not applicable

FUTURE CONSIDERATIONS

This long-term study on stand development will continue to be monitored. These comments are based on observations while collecting data for this study and experience with other harvests in similar forests in this area. We anticipate yellow-poplar to continue to dominate on the better sites, but some density-dependent, self-thinning will occur. On the poor productivity sites that are more stressful, yellow-poplar will probably diminish compared to other species. Oaks and hickories are better suited to these sites and probably will be able to persist and become a greater proportion of the overstory component replacing many of the yellow-poplar. Black cherry in this area is susceptible to pitch pockets, black

Table 3—Most dominant tree by species on each subplot (n = 120) after 10 years regardless of treatment for the pre- and post-treatment site preparation regeneration study at the Forest Resources Research and Education Center, Oak Ridge, TN

Species	Number of Subplots	Percent of Total
Yellow-poplar	46	38
Black cherry	27	22
Virginia pine	19	16
Red maple	8	7
Hickories	7	6
Oaks	6	5
Miscellaneous species[a]	7	6

[a]Sweetgum, sourwood, elms, white ash.

rot and crown breakage from wind and ice damage. We do not expect black cherry to be a formidable component of the overstory.

The role of red maple is unknown. There are twice as many stems of red maple compared to oaks. However, sawtimber red maple was an infrequent component of the harvested stand. Although the number of subplots with dominating oaks and red maple was similar, our observations and experiences are that red maple rarely assumes a dominant position in mixed hardwood stands in TN. Most of the red maple and the miscellaneous species are below the main canopy comprising the midstory and will minimally influence the overstory species.

Future work is to use this dataset of initial preharvest measurements and 10 year post-harvest measurements for the various site preparation treatments to evaluate the predictive ability of the hardwood regeneration model developed for the Appalachian forests by forest researchers at the Bent Creek Experimental Forest and to modify the model for application to forests in east Tennessee.

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PRODUCTION OF WILLOW OAK ACORNS IN AN ARKANSAS GREENTREE RESERVOIR: AN EVALUATION OF REGENERATION AND WATERFOWL FORAGE POTENTIAL

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Abstract—Greentree reservoirs (GTRs) provide critical habitat for a broad suite of species. Unfortunately, many GTRs are mismanaged, leading to undesirable successional changes and possible habitat degradation. This study evaluates willow oak acorn production in terms of the potential for natural regeneration and waterfowl forage. During the fall and winter of 2004 and 2005, acorns were collected biweekly from 40 overstory willow oaks distributed throughout the study site. Once collected, acorns were subjected to a float test and counted. During both years of the study, production of sound acorns was well above the generally accepted giving-up density of 50 kg/ha of forage for waterfowl. Further, comparing germination rates observed at the study site to those predicted in the literature indicates that willow oak acorns are germinating at a higher rate than expected. This study further emphasizes the importance of gaining a better understanding of artificially flooded hardwood systems.

INTRODUCTION

The practice of managing bottomland hardwood stands as greentree reservoirs (GTRs) began in the late 1930s in the area around Stuttgart, AR (Rudolph and Hunter 1964). The primary objective of GTR management is to replace the natural flooding regime of a bottomland hardwood stand with a more reliable flooding regime in order to consistently provide habitat for migrating waterfowl and subsequently provide waterfowl hunting opportunities (Fredrickson 2005, Fredrickson and Batema 1992, Hertlein and Gates 2005, King and Allen 1996). Following the initiation of the practice in AR, GTR management spread throughout numerous states in the Southeastern and Northeastern United States with most states within the Mississippi Alluvial Valley having GTRs by 1963 (Fredrickson and Batema 1992). The basis for this popularity was likely the perception that GTR management benefited waterfowl and waterfowl hunters without any adverse effects on the timber (Fredrickson and Batema 1992, Rudolph and Hunter 1964). Some early studies found beneficial effects related to annual flooding and GTR management (Merz and Brakhage 1964, Broadfoot and Williston 1973). However, more recent studies have documented numerous detrimental effects attributable to GTR management (Hertlein and Gates 2005, King 1995, Malecki and others 1983, Schlaegel 1984, Wigley and Filer 1989).

In their survey of GTR managers, Wigley and Filer (1989) found that 95 percent of GTRs, both publicly and privately owned, were flooded every year. From their survey, the authors were able to identify several common problems associated with GTR management. These problems included low regeneration of seedlings and saplings of desirable species, increased overstory tree mortality, wind-throw, crown dieback, basal swelling, scarring by beaver, and excessive sedimentation. Problems occurred most often in GTRs with dominant timber at least 60 years old.

According to Fredrickson and Batema (1992), waterfowl readily consume fully developed acorns with little insect damage; however, waterfowl rarely consume damaged, deformed, or aborted acorns. McQuilkin and Musbach (1977) found no difference in the production of sound pin oak (*Quercus palustris*) acorns in GTRs compared to nonflooded areas. They did, however, find fewer acorns were damaged by insects in GTRs. Reduced acorn damage in GTRs is attributed to the fact that nut weevils (*Curculio* spp.) overwinter in the soil (Brezner 1960) and are thereby killed by long-term dormant season flooding. Karr and others (1990) found a slight increase in cherrybark oak (*Quercus pagoda*) acorn production in GTRs. Similar to the results of McQuilkin and Musbach (1977), Karr and others (1990) found decreased acorn damage by weevils in GTRs.

Merz and Brakhage (1964) found total pin oak acorn production did not differ between naturally and artificially flooded areas. However, they did find trees in the flooded area produced more sound acorns than did trees in unflooded plots. Despite more sound acorns having been produced in flooded areas, Merz and Brakhage (1964) found that in flooded areas, only 1 seedling became established for every 2,100 acorns, compared to 1 established seedling for every 26 acorns in unflooded areas. The authors state that increased consumption by waterfowl largely accounted for the difference in seedling establishment. In contrast to other studies, Francis (1983) found Nuttall oak (*Quercus nuttallii*) in unflooded areas produced approximately twice as many acorns as Nuttall oaks in a GTR.

In general, acorn production for most oak species is highly variable within and among years and species (Dey 1995, Greenberg 2000, Koenig and others 1994). Numerous studies have investigated the role of biotic and abiotic factors on acorn production (Cecich and Sullivan 1999, Francis 1983, Goodrum and others 1971, Greenberg 2000, Perry and others 2004, Stelzer and others 2004); however, the

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full range of mechanisms influencing acorn production are still not fully understood. Perry and others (2004) found a significant linear relationship between mast production and basal area for two white oak (Leucobalanus) species. However, the authors found no linear relationship existed between acorn production and basal area for red oak (Erythrobalanus) species in the Ouachita Mountains, AR. Francis (1983) found thinning did not affect acorn production, but flooding and tree size did. On average, trees in flooded areas produced fewer acorns than trees on nonflooded areas, and larger trees typically produced more acorns than smaller trees. Cecich and Sullivan (1999) found relative humidity contributed significantly to the variation in white oak (*Quercus alba*) acorn production but not to black oak (*Quercus velutina*). Rain positively affected black oak flower survival but had no effect on white oak. Fog had a positive effect on flower survival for both species.

The production of acorns varies greatly by species (Dey 1995). Species such as sessile oak (*Quercus petraea*) may not begin to produce acorns until trees are 40 years old; whereas, Nuttall oak and sawtooth oak (*Quercus acutissima*) may produce an acorn crop as early as age five. Further, numerous species of oak can be expected to produce acorn crops on a 1 to 2 year interval, while other species may have intervals of up to 5 to 7 years or even 4 to 10 years (Young and Young 1992). According to Young and Young (1992), willow oaks (*Quercus phellos* L.) may produce their first acorn crop around age 20, and on average, produce on a 1-year interval. Several studies have found the average weight of a fresh willow oak acorn to be approximately 1 gram (Goodrum and others 1971, Young and Young 1992).

McQuilkin and Musbach (1977) found the number of underdeveloped acorns and insect-infected acorns varied little between years for pin oaks growing in a GTR. Further, the authors estimated that waterfowl only consume sound, fully developed acorns in significant numbers. It is estimated that a minimum of 50 kg/ha of acorns is required for waterfowl to forage efficiently (pers. comm., R.M. Kaminski, Mississippi State University, Department of Wildlife and Fisheries). Below this threshold, the energetic expenses related with foraging outweigh the benefits and waterfowl will cease to forage on an area. Many acorns never become available for waterfowl forage or natural regeneration due to being consumed prior to falling. Cypert and Webster (1948) estimated that canopy-dwelling birds consumed approximately 13 percent of the acorns from willow oak and water oak (*Quercus nigra* L.) trees. Similarly, Korschgen (1954) estimated arboreal feeders consumed 14 percent of mature acorns.

STUDY AREA

This study was conducted in a 291-ha GTR located in Arkansas County, AR, approximately 8 km south of Stuttgart, AR. The dominant soil on the area is Perry clay (approximately 83 percent of the area). Other soils found on the area are Dewitt silt loam (13.2 percent) and Stuttgart silt loam (3.7 percent). Soil pH ranged from 5.3 for the Dewitt silt loam to 5.8 for the Perry clay (NRCS web soil survey, http://websoilsurvey.nrcs.usda.gov/app/).

The management practices applied to the GTR currently, and historically, were to flood the entire area annually. The primary objective of managing this GTR was to provide opportunities to hunt migrating waterfowl. The average flooding depth across the area was 34.6 cm. Flooding was typically initiated in mid-October to ensure that there was an adequate amount of aboveground water in the GTR by the time migrating waterfowl began moving through the area. The actual initiation date varied considerably from year to year due to climatic conditions. In the fall of 2004, flooding was initiated between September 20 and November 20 for the various compartments within the stand. Similarly, flooding initiation occurred between September 20 and December 9 for the fall of 2005.

METHODS

Field Methods

In September 2004, 40 acorn traps were established throughout the GTR. Acorn collection traps consisted of four 1.52 m pieces of metal conduit for legs, a square frame (area = 1 m^2) constructed from treated lumber, a catchment area made of plastic netting, and a plastic collection bottle. Trap locations were selected using sample points from an earlier vegetation analysis study (Guttery and Ezell 2005). Points were selected such that the entire GTR was sampled relatively evenly. At each point, an acorn trap was erected under the overstory willow oak nearest to plot center. Traps were placed in a random direction halfway between the bole and the edge of the canopy of selected trees. At each selected tree, the diameter at breast height (d.b.h.) and the crown radius in each cardinal direction was recorded. Once traps were established, acorns were collected approximately every 14 days during the time acorns were falling for 2004 and 2005. In 2004, acorns were collected six times between October 2 and December 11. In 2005, acorns were collected seven times between October 1, 2005 and January 14, 2006. For the 2005 collection, acorns were only collected from 38 of the original 40 traps because one sample tree died and one trap suffered irreparable damage. Collected acorns were subjected to a float test to determine the number of sound and “bad” acorns per trap. “Bad” acorns were the result of insect infestation, being aborted by the tree, and damage by arboreal feeders.

Analyses

Prior to analysis, sample trees were grouped into 5-cm diameter classes. Sample trees ranged in d.b.h. from 35 to 85 cm, with the majority of stems falling between 45 and 65 cm. Then, using vegetation inventory data (Guttery and Ezell 2005), the average number of overstory willow oak trees/ha was calculated, as divided into 5-cm diameter classes. Willow oak diameters across the entire GTR ranged from 20 to 110 cm, with the majority (>75 percent) of stems ranging from 40 to 65 cm.

Using the average crown radius, the 2-dimensional area of each sample tree’s crown was estimated. Since each acorn trap was of a known area (1 m^2), it was possible to calculate a blow-up factor to extrapolate acorn production across the entire crown of each sample tree. In doing this, it is assumed that the area sampled was representative of the entire crown. Production of sound, bad, and total acorns for each tree was then calculated across both collection years. Finally, the average production of sound, bad, and total acorns for each diameter class was calculated. Using a random sample of sound acorns (n=585 acorns) collected during the 2005 collection period, the average weight of a single willow oak acorn was determined. This weight was used to calculate the number of sound acorns required to weigh 1 kg. This allowed for the average weight of sound acorns within each diameter class to be calculated. Finally, using trees/ha (Guttery and Ezell, 2005), the total production of sound, bad, and total acorns was estimated by diameter class across the entire GTR. In order to investigate the variability of acorn production, the average acorn production per tree as well as measures of variability were calculated (PROC MEANS, SAS Institute 2004). In performing all these calculations, it is assumed that the trees sampled were representative of overstory willow oak trees across the entire GTR.

RESULTS

Acorn production for both 2004 and 2005 varied considerably both for total production and among diameter classes. Results of the average total acorn production by diameter class are found in table 1. For both 2004 and 2005, the 35 and 85 cm diameter classes produced, on average, the fewest total acorns per ha. Low acorn production in these diameter classes could be a function of these diameter classes having the fewest number of trees/ha, low acorn production per tree, or both. In 2004, trees between 55 and 65 cm produced 60 percent of the acorns based on diameter classes sampled. In 2005, these three diameter classes produced only 45 percent of the total acorns based on diameter classes sampled. For both years, the 75 cm diameter class produced a considerable number of acorns (90,615 and 54,596, respectively), while both the 70 and 85 cm diameter classes produced far fewer in both years. For both total production and for 7 of the 10 diameter classes, total acorn production was greater in 2004 than in 2005.

Similar to total acorn production, the production of sound acorns varied greatly between years and diameter classes (table 2). With an average of 301,667 sound acorns per hectare for the 10 diameter classes sampled, production for 2004 was considerably better than 2005 (159,304 sound acorns per hectare). The diameter classes of 55 cm through 65 cm produced 58 percent of the sound acorns in 2004 and 61 percent of the sound acorns in 2005. For both years, sound acorn production was found to be least for the 35 and 85 cm diameter classes. This finding is not surprising since these diameter classes had the lowest total acorn production. As with the total acorn production, sound acorn production within the 75 cm diameter class was unusually high compared to adjacent diameter classes for both years. Data in table 2 also show the average weight (kg/ha) of sound acorns by diameter class. For both years, total average production far exceeded the minimum of 50 kg/ha needed to support waterfowl.

The production of bad acorns exhibited some of the same patterns as the total and sound acorn production (table 3). For bad acorns, average acorn production was lowest for the smallest and largest trees for both years (similar to total acorn production and sound acorn production). Also, the 75 cm diameter class produced considerably more bad acorns than adjacent diameter classes in both years. Data from 2004 sampling show 62 percent of the bad acorns were produced by trees in the 55 through 65 cm diameter classes. However, in 2005 these diameter classes only produced 32 percent

Table 1—Average total acorn production by diameter class, 2004 and 2005.

Year	Diameter (cm)	Trees Sampled	Trees/ha	Total Acorns / ha	Standard Error
2004					
	35	1	2.7	113	_
	40	2	5.2	10223	1462
	45	8	6.3	36974	2244
	50	5	6.4	32943	1235
	55	5	5.8	63973	4018
	60	6	4.5	135537	13362
	65	9	3.7	62398	6827
	70	2	1.8	6951	983
	75	1	1.5	90615	_
	85	1	0.4	1769	_
	Overall	40	41.4	555671	3088
2005					
	35	1	2.7	113	_
	40	2	5.2	58573	11119
	45	7	6.3	43779	3474
	50	5	6.4	25325	520
	55	5	5.8	59015	2369
	60	6	4.5	54054	5084
	65	8	3.7	51030	3263
	70	2	1.8	15487	2297
	75	1	1.5	54596	_
	85	1	0.4	1327	_

Table 2—Average total sound acorn production by diameter class, 2004 and 2005

Year	Diameter (cm)	Trees Sampled	Trees/ha	Sound Acorns / ha	Standard Error	Percent of Total	Mass (kg/ha)
2004							
	35	1	2.7	113	_	100	0.1018
	40	2	5.2	1513	199	14.8	1.3631
	45	8	6.3	27522	1967	74.4	24.795
	50	5	6.4	19826	785	60.2	17.861
	55	5	5.8	50568	3348	79.0	45.557
	60	6	4.5	93846	11599	69.2	84.546
	65	9	3.7	31290	2489	50.1	28.189
	70	2	1.8	5963	434	85.8	5.3721
	75	1	1.5	70142	_	77.4	63.191
	85	1	0.4	884	_	50.0	0.7964
	Overall	40	41.4	363794	2250	65.5	327.74
2005							
	35	1	2.7	0	_	0.0	0
	40	2	5.2	7597	1232	13.0	6.8441
	45	7	6.3	8538	541	19.5	7.6919
	50	5	6.4	11223	668	44.3	10.111
	55	5	5.8	33917	1500	57.5	30.556
	60	6	4.5	28824	3258	53.3	25.968
	65	8	3.7	33929	2659	66.5	30.567
	70	2	1.8	7219	926	46.6	6.5036
	75	1	1.5	27299	_	50.0	24.594
	85	1	0.4	758	_	57.1	0.6829
	Overall	38	41.4	207352	971	49.6	186.8

of the bad acorns. Trees in the 40 through 50 cm diameter classes produced 50 percent of the bad acorns produced by trees in the diameter classes sampled for 2005.

DISCUSSION

Auchmoody and others (1993) classified northern red oak (*Quercus rubra*) acorn crops of between 309,000 and 618,000 acorns/ha to be "good" crops. Using this criterion, willow oaks in this GTR experienced "good" crops during both years of this study (table 1). However, the ecology and biology of northern red oak and willow oak differ considerably, and therefore these numbers may not be equally meaningful for willow oak acorn production. Overall average acorn production during this study was 486,885 acorns/ha. This finding is considerably higher than the 12 year average production of 356,700 pin oak acorns per hectare reported by McQuilkin and Musbach (1977).

These results show considerable variation in total acorn production, as well as production by diameter class and for individual trees, both within and between years. Numerous studies have documented the variation in acorn production (Beck 1977, Downs and McQuilkin 1944, Koenig and others 1994, Sork and others 1993). Young and Young (1992) state that willow oaks typically produce an acorn crop every year. Although this study only presents two years of data, the findings indicate that willow oak in this GTR may be consistently producing acorn crops. The fact that 33 of the 38 trees sampled in both years exhibited greater than a 20 percent difference in total acorns produced between the two years indicates that, for the most part, acorn production per tree varies considerably. However, the fact that total acorn production per hectare was high for both years indicates that while individual trees may not produce consistently, the willow oak population does seem to produce well each year. Again, these statements are based on two years data so long-term trends can only be speculated.

Overall, the production of sound acorns per tree in both 2004 and 2005 was less variable than was total acorn production per hectare. However, 32 sample trees had sound acorn production that varied by greater than 20 percent, compared to 33 trees for total acorn production. Table 2 shows that overall production of sound acorns per tree varied less in 2005 (SE=971) than in 2004 (SE=2 250). Although production was highly variable between years and among diameter classes, no obvious patterns in variability were observed, indicating that either no relationship exists between diameter and acorn production or more years of monitoring are needed to assess the relationship.

Approximately 35 percent of the acorns produced in 2004 were bad, compared to approximately 50 percent in 2005. Although there appears to be a considerable difference in the production of total bad acorns between 2004 and 2005, the difference was actually less than 20 000 acorns (table 3). For both years of the study, the overall variability in bad acorn production was considerably lower than the variability of total acorn production and equal to or less than the variability in sound acorn production. This seems to indicate that the overall production of bad acorns was relatively constant. Similarly, McQuilkin and Musbach (1977) report a smaller range in the number of underdeveloped/aborted acorns and insect infested acorns than for total acorn production. These authors concluded that regardless of crop size, a similar number of underdeveloped/aborted and insect infested acorns are produced each year.

Table 3—Average total bad acorn production by diameter class, 2004 and 2005

Year	Diameter (cm)	Trees Sampled	Trees/ha	Bad Acorns / ha	Standard Error	Percent of Total
2004						
	35	1	2.7	0	_	0.0
	40	2	5.2	8710	1263	85.2
	45	8	6.3	9452	659	25.6
	50	5	6.4	13116	584	39.8
	55	5	5.8	13405	680	21.0
	60	6	4.5	41691	4063	30.8
	65	9	3.7	31108	5253	49.9
	70	2	1.8	987	549	14.2
	75	1	1.5	20474	_	22.6
	85	1	0.4	884	_	50.0
	Overall	40	41.4	191856	1405	34.5
2005						
	35	1	2.7	113	_	100
	40	2	5.2	56173	9887	87.0
	45	7	6.3	35242	3034	80.5
	50	5	6.4	14103	235	55.7
	55	5	5.8	25099	914	42.5
	60	6	4.5	25228	2341	46.7
	65	8	3.7	17101	984	33.5
	70	2	1.8	8267	3222	53.4
	75	1	1.5	27299	_	50.0
	85	1	0.4	569	_	42.9
	Overall	38	41.4	210188	917	50.4

In 2004, approximately 65.5 percent of the estimated total acorns per hectare were sound. This percentage equates to an estimated 328 kg/ha of sound acorns (table 2). Production of sound acorns in 2005 declined considerably to only 50 percent of the total production and an average of 207,352 sound acorns per hectare (187 kg/ha). Per hectare levels of production far exceed the minimum requirement of 50 kg/ha necessary to sustain waterfowl on an area. Given the average weight of a single willow oak acorn for this GTR, if it is assumed that waterfowl do reduce acorn abundance to 50 kg/ha then there should be approximately 55,000 sound acorns remaining that could potentially germinate. Applying the germination rate for acorns in artificially flooded areas reported by Merz and Brakhage (1964), an average of 26 established willow oak seedlings/ha would be expected. Guttery and Ezell (2005) found an average of 210 willow oak seedlings/ha that were less that 0.3 m tall in this GTR (one seedling for every 264 sound acorns), indicating that either waterfowl are not consuming large quantities of willow oak acorns or germination rates are unusually high.

CONCLUSIONS AND RECOMMENDATIONS

The results of this study are similar to the findings of several other studies. Overall, acorn production could be considered "good" in both 2004 and 2005. It should be noted that the numbers reported here are likely to be below actual production levels, since calculations did not include a correction for acorns which may have been consumed by birds and rodents while in the trap or on the tree. The production of sound acorns appears to be sufficient to support waterfowl while still allowing for some willow oak regeneration. Acorn production was good despite the artificial flooding regime imposed upon this site, and damage to acorns by insects was likely reduced due to flooding. Although flooding does not appear to be negatively impacting acorn production, it is likely having a substantial affect on willow oak regeneration. King (1994) found that acorns submerged in water for 90 days exhibited significantly lower rates of germination compared to nonflooded acorns. This, along with seedlings often being flooded prior to dormancy, is likely limiting willow oak regeneration on this site. Therefore, an altered flooding regime could be beneficial in efforts to regenerate this GTR naturally. Since red oak acorns take two years to mature, good acorn crops can be anticipated as much as a year in advance through visual surveys (Gysel 1956). By flooding the GTR during the year preceding an anticipated good acorn crop, nut weevil populations can be greatly reduced, therefore limiting the amount of damage to sound acorns by weevils. Allowing the GTR, or areas in the GTR, to remain unflooded, or flooded only briefly during the dormant season, for two or more years thereafter it is likely that ample willow oak regeneration will be able to establish and grow to heights greater than mean flooding depth. Finally, controlling undesirable midstory species may create light conditions more conducive to oak regeneration (Guttery 2006).

The desire to regenerate oaks in artificially flooded areas while also managing for waterfowl gives rise to new questions and concerns for managers and researchers. First, studies have not conclusively shown that waterfowl select particular GTRs based on the availability of acorn forage. It is possible that the primary role of GTRs for waterfowl is to provide cover rather than to provide food (forage versus cover hypothesis). Second, many waterfowl species seem to prefer open park-like stands. Dense regeneration could make stands less desirable to waterfowl; however, studies have not been conducted to determine if this truly is the case. Therefore, until these questions can be resolved the issue of managing GTRs may be even more complex than previously thought. If acorn production is a major factor influencing waterfowl use of GTRs then it is necessary to ensure that mast producing trees continue to exist in these areas. However, management activities aimed at promoting oak regeneration may result in stands being less desirable for waterfowl. If in fact forage availability is of lesser importance than cover, then species composition may not matter for waterfowl, but decreased biodiversity resulting from a shift in composition to all highly flood tolerant tree species will likely be detrimental to many other faunal species.

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BIOMASS ACCUMULATION PATTERNS OF NUTTALL OAK SEEDLINGS ESTABLISHED UNDER THREE STAND CONDITIONS

Emile S. Gardiner and Benjamin P. Hogue[1]

Abstract—To gain a better understanding of bottomland oak seedling development under various stand conditions, we studied biomass accumulation on 1-0 bareroot Nuttall oak (*Quercus nuttallii* Palm.) seedlings planted in a mature bottomland hardwood stand after harvesting. Harvest operations in fall 1998 created three residual stand conditions which applied treatment conditions that left overstory residual stocking levels of 0, 25, and 50 percent. During the third growing season, we randomly selected eight plants from each stand condition, excavating and separating them into leaf, stem and root tissues. We used oven-dried mass to calculate leaf weight ratio, stem weight ratio and root weight ratio for each sample plant. Our findings indicate that, regardless of stand condition, artificially established Nuttall oak seedlings differed little in biomass accumulation and distribution of accumulated biomass among tissues. While trends in the data indicate that seedlings established under zero percent stocking tended to increase biomass accumulation, high error terms associated with treatment means precluded definitive delineation of differences in seedling biomass accumulation among tissue types under the various stand conditions. However, root weight ratios and stem weight ratios suggest that seedlings established beneath partial canopies may have experienced more moisture stress than seedlings established under zero percent stocking.

INTRODUCTION

Silviculturists have yet to develop reliable practices for regenerating bottomland hardwood stands that produce an adequate component of the highly desired bottomland oaks (*Quercus* spp.). Several factors may contribute to the difficulty of developing sufficient advance oak reproduction in bottomland stands, one of which may be related to the structure of mature stands (Oliver and others 2005). Mature bottomland hardwood stands often have an intact overstory and a dense midstory layer that together can reduce light availability in the understory to less than 10 percent of full sunlight (Gardiner and Yeiser 2006, Lockhart and others 2000). While acorns are able to germinate, evidence suggests that seedling growth and survival may be limited by the understory light regime (Gardiner and Hodges 1998, Hodges and Gardiner 1993). Accordingly, workers often identify insufficient light as a primary factor limiting growth of advance oak reproduction in mature bottomland hardwood stands.

Evidence of the potential for light to limit bottomland oak seedling growth has been demonstrated by Gardiner and Hodges (1998), and Guo and others (2001). Gardiner and Hodges (1998), who studied cherrybark oak (*Quercus pagoda* Raf.) seedling biomass accumulation under controlled levels of light, reported that cherrybark oak seedlings exhibited a quadratic response to light availability. Greatest biomass accumulation occurred under moderate light levels (27-53 percent of full sunlight), and relatively low and high light availabilities resulted in diminished biomass accumulation (Gardiner and Hodges 1998). The decreased biomass accumulation under low light availability was attributed to insufficient photosynthetically active radiation, whereas decreased biomass accumulation under full sunlight was attributed to moisture stress.

Silvicultural practices to reduce canopy cover and increase understory light availability have been successfully applied in bottomland hardwood stands. Such practices have spanned a range of intensities—from midstory removals, gap formation, and partial stand harvests. Midstory removals generally target stems subordinate to the overstory leaving the canopy intact; gaps typically are formed by removing canopy vegetation in small (≤ 0.5 ha) areas of the stand; and partial harvesting may remove a range of basal area from the stand, often leaving relatively few residual stems to form a sparse canopy. Although practitioners have an array of options for influencing the light environment in the understory of mature bottomland hardwood stands, we lack an understanding of how bottomland oak seedlings develop under differing stand conditions that result in various understory light regimes.

Our purpose was to quantify biomass accumulation and distribution among tissue types for Nuttall oak (*Quercus nuttallii* Palm.) seedlings, which were artificially established under three stand-stocking levels. We hypothesized that seedlings established under the various stocking levels would show differing responses to light availability, e.g., those established under partial canopies would exhibit increased biomass accumulation and a more balanced distribution of biomass among root and stem tissues than seedlings established in the open.

METHODS

The study was conducted in a mixed-species bottomland hardwood stand located about 10 km east of Anguilla in Sharkey County, MS (32° 58' N, 90° 43' W). In fall 1998, we sectioned the stand into two blocks, each having three, 1.7-ha experimental plots that were assigned one of three residual stocking levels. Using tables published by Goelz (1995), we then harvested trees on the plots to their assigned treatment level, which included 0 percent residual stocking, 25 percent residual stocking or 50 percent residual stocking. Harvesting

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operations were conducted using conventional chainsaw felling, and merchantable logs were removed from the site with a grapple skidder. After harvesting, the site was prepared for planting by severing at groundline with a chainsaw all stems greater than 2.5 cm diameter at breast height (d.b.h.) that were not marked as leave trees. Site preparation also included reducing slash piles to the ground by cutting upright branches from felled crowns. The stand was planted by hand in March 1999 with 1-0 bareroot Nuttall oak seedlings obtained from the Mississippi Forestry Commission Nursery in Winona, MS. Residual stand conditions following the harvest are listed in table 1, and a more detailed description of the site, stand, harvest levels, and planting methods can be found in Ware and Gardiner (2004).

We sampled Nuttall oak seedling biomass in the summer of 2002 by randomly selecting eight seedlings from each treatment plot in a randomly chosen block. Each sample seedling (24 total) was excavated by hand and dissected into root, stem and leaf tissues. Though we would have preferred to sample more seedlings in each treatment plot, we were limited by the time required to properly excavate sample seedlings. In the course of this study, two technicians worked three months to excavate the 24 sample seedlings. Soil was washed away from excavated root tissues and all tissue types were oven-dried at 70 °C before dry mass was measured on a balance. The relative distribution of mass among each tissue type was calculated with the following equations. Leaf weight ratio (LWR) = leaf mass ÷ total seedling mass; stem weight ratio (SWR) = stem mass ÷ total seedling mass; root weight ratio (RWR) = root mass ÷ total seedling mass.

Response variables, including leaf mass, stem mass, root mass, total seedling mass, LWR, SWR and RWR, were analyzed according to a completely random design. Analysis of variance was performed and Duncan's Multiple Range Test was used to separate treatment means. All tests were conducted at an alpha of 0.05.

RESULTS AND DISCUSSION

Seedling Establishment

Third-year findings on survival, height and diameter growth of Nuttall oak seedlings planted under the three residual stand stocking levels are reported in Ware and Gardiner (2004). In brief, third-year survival averaged 77 percent for all treatments, and this survival resulted in more than 570 established seedlings per hectare across the study site (Ware and Gardiner 2004). Height growth was greatest on seedlings established under 0 percent residual canopy where they were 59 percent taller (mean height = 152 cm) than seedlings established under the 25 and 50 percent residual stocking treatments (Ware and Gardiner 2004). Root-collar diameter growth tracked height growth as Nuttall oak seedlings established under zero percent stocking showed diameters 45 percent greater (mean diameter = 17.8 mm) than seedlings established under 25 and 50 percent residual stocking (Ware and Gardiner 2004).

Seedling Biomass Accumulation

Though Ware and Gardiner (2004) observed differences in height and root-collar diameter growth, dry mass within tissue types did not vary for Nuttall oak seedlings established under three stand stocking levels (fig. 1). Three years after outplanting, average seedling mass was 138.2 ± 36.9 g; root tissue comprised 38 percent, stem tissue comprised 50 percent and leaf tissue comprised 12 percent of total seedling mass (fig. 2). Mean seedling and tissue weights appeared to increase with decreasing stand stocking (figs. 1, 2). However, these trends were not significant, and treatment differences may have been obscured by high error terms associated with treatment means. Regardless of statistical significance, the response observed in our data for Nuttall oak did not follow the pattern observed for cherrybark oak raised under neutral density shade cloth (Gardiner and Hodges 1998).

Seedling Biomass Distribution

Nuttall oak seedlings established under the various stand stocking levels did show differing proportions of biomass distributed among root and stem tissues (fig. 3). Seedlings established under zero percent stocking showed a 36 percent higher SWR than seedlings established under the 25 and 50 percent stocking levels (fig. 3). The RWR for seedlings established under zero percent stocking was 25 percent less than RWRs of seedlings raised under 25 percent stocking (fig. 3). Three years after establishment, Nuttall oak seedlings raised under the various stand stocking levels accumulated similar proportions of biomass in leaf tissue (fig. 3).

Our findings appear contrary to reported biomass accumulation patterns of other oak species established

Table 1—Residual stand conditions following three levels of overstory removal in a mixed-species bottomland hardwood stand, Sharkey County, MS

	Target stocking level		
Variable[a]	0 %	25 %	50 %
Trees per hectare	0	39	89
Mean stem diameter (cm)	-	48.8	46.8
Basal Area (m^2 ha^{-1})	0	7.6	15.37
Stocking per hectare (%)	0	26	53

[a] Residual stand data cited from Ware and Gardiner (2004).

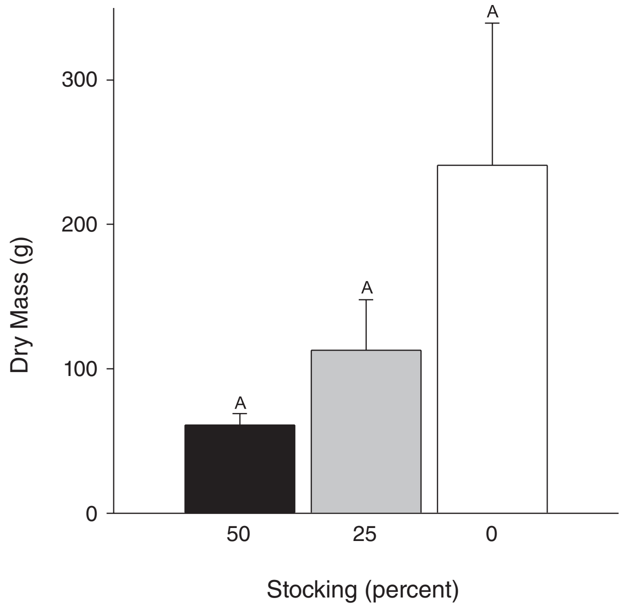

Figure 1—Mean dry mass of Nuttall oak seedlings 3 years after outplanting under 0, 25, or 50 percent stocking, Sharkey County, MS. Standard error bars with the same letter are not significant at the 0.05 probability level.

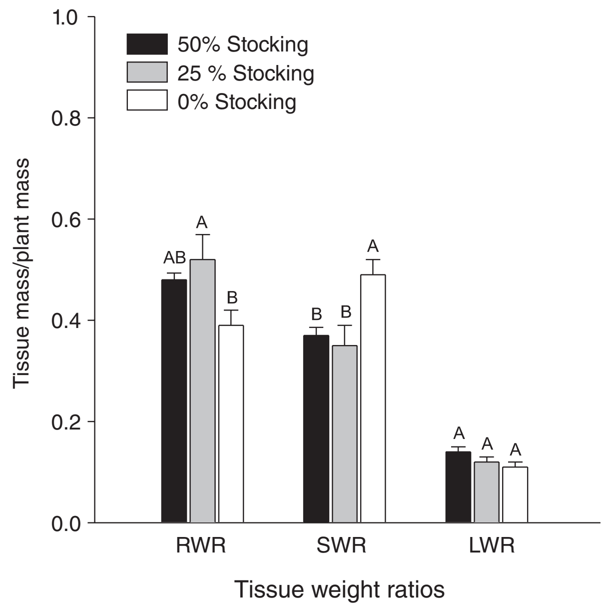

Figure 3—Mean root weight ratios (RWR), stem weight ratios (SWR) and leaf weight ratios (LWR) for Nuttall oak seedlings 3 years after outplanting under 0, 25, or 50 percent stocking, Sharkey County, MS. Mean comparisons are for a given tissue type, and standard error bars with the same letter are not significant at the 0.05 probability level.

under environments of partial sunlight. Research on cherrybark oak seedlings illustrates that this species exhibits a quadratic response to light availability, such that the greatest biomass accumulation occurs under moderate light levels, whereas extremely low or high light availability results in diminished biomass accumulation (Gardiner and Hodges 1998, Guo and others 2001). Ziegenhagen and Kausch (1995) reported a similar growth response by pedunculate oak (*Quercus robur* L.) grown under neutral density shade cloth in Germany. Based on the findings reported for these other oak species, we expected Nuttall oak to exhibit greatest biomass accumulation and a relatively balanced distribution of root and stem tissues in treatments that retained residual stocking. These were not our observations, and our diverging results may have arisen from at least three different factors.

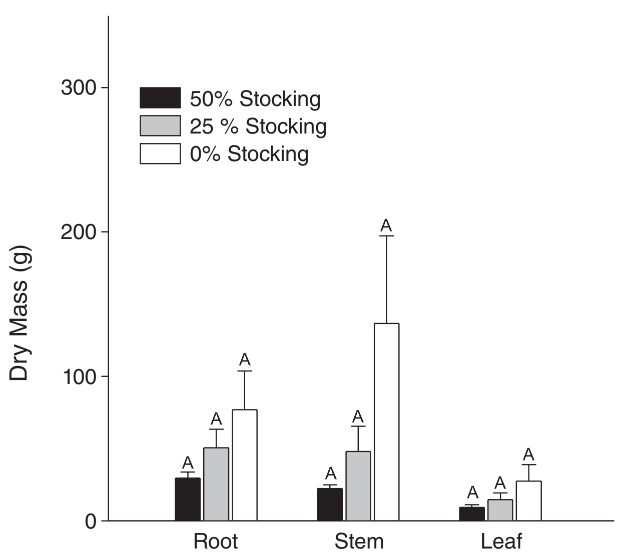

Figure 2—Mean dry mass of root, stem and leaf tissues for Nuttall oak seedlings 3 years after outplanting under 0, 25, or 50 percent stocking, Sharkey County, MS. Mean comparisons are for a given tissue type, and standard error bars with the same letter are not significant at the 0.05 probability level.

A fundamental difference between the light environment in the understory of a natural bottomland hardwood stand and the light environment in the controlled studies of Gardiner and Hodges (1998) and Ziegenhagen and Kausch (1995) is light quality. In addition to reducing the quantity of photosynthetically active radiation incident in the understory, hardwood forest canopies alter light quality by reducing the red:far-red ratio of the spectrum (Kozlowski and others 1991). Neutral density shade cloth, such as used by researchers in controlled experiments, effectively reduces light quantity, but does not impact light quality. Thus, it is possible that growth of seedlings established in the partially harvested plots in this study was impacted by the decrease in light availability as well as altered light quality.

However, altered light quality may not sufficiently explain the results we observed. First, the partially harvested plots in this study, particularly plots that retained 25 percent residual stocking, had canopies that were sparse enough to allow direct sunlight to comprise a substantial proportion of the radiation received by underplanted seedlings. Additionally, a reduced red:far-red ratio, which is typical of deep shade environments, generally induces a shift in carbon allocation away from the root system in favor of the shoot. This was not observed in our study, as Nuttall oak seedlings established under partial canopies showed a preference for biomass accumulation in root tissue.

Secondly, light availability may impact carbon allocation in Nuttall oak differently than other bottomland oaks. Earlier research illustrated that Nuttall oak leaf physiology responds markedly different to light availability than does cherrybark oak and overcup oak (*Quercus lyrata* Walt.) (Gardiner 2002). As differences in leaf physiology among species have been identified, it is reasonable to conclude that various oak species may exhibit a range of developmental strategies that lead to differing morphologies relative to light availability. In support of this argument, Long and Jones (1996) reported that oak species endemic to the southern United States showed inherently different growth strategies that led to contrasting morphologies during the establishment year.

Finally, factors other than light availability, particularly moisture stress, may have limited carbon assimilation and altered biomass accumulation patterns of the underplanted oak seedlings. Evidence for this explanation is provided by our observations of the SWRs and RWRs of seedlings we sampled. Our results indicate that seedlings established beneath 25 and 50 percent stocking favored root growth over stem growth. Favoring biomass accumulation in roots over shoots has been attributed to moisture stress in seedlings of other oak species (Canadell and Rodà 1991, Kolb and Steiner 1990). We expected the residual overstory in partially harvested plots to moderate understory vapor pressure deficits and reduce transpiration of underplanted seedlings. However, it is possible that the residual trees in partially harvested plots provided substantial below-ground competition which could have resulted in high moisture stress of the underplanted seedlings.

CONCLUSIONS

Reliable practices for reproducing bottomland oaks in existing hardwood stands currently are not available. While a range of practices can be applied to increase understory light availability, appropriate stand structures for improving growth of bottomland hardwood reproduction have not been identified. We examined biomass accumulation of Nuttall oak seedlings artificially established beneath three levels of residual stand stocking. Based on our findings, stand stocking level did not influence Nuttall oak seedling establishment or biomass accumulation. An earlier report from this study site indicated that Nuttall oak could be successfully underplanted beneath a range of stand densities (Ware and Gardiner 2004). Findings from this research are generally in agreement with the findings of Ware and Gardiner (2004).

However, high error terms associated with treatment means in this study may have masked differences, and trends observed in the data may become more prominent over time. We did observe that stand stocking altered the proportional distribution of biomass among root and stem tissues. Seedlings established under zero percent stocking showed the greatest proportion of biomass accumulated in stem tissue, while seedlings raised under 25 percent stocking showed the greatest proportion of biomass accumulated in root tissue. These findings suggest that Nuttall oak seedlings planted in the understory of partially harvested stands may have experienced substantial moisture stress.

Notably, our field observations for Nuttall oak contrast with previously reported biomass distribution patterns for other oak species raised under more controlled light environments. Our findings warrant additional research investigating interactions between light availability and competition associated with stand structure in bottomland hardwood forests.

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HICKORY REGENERATION UNDER FIVE SILVICULTURAL PRESCRIPTIONS IN AN OAK-HICKORY FOREST IN NORTHERN ALABAMA

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Abstract—Hickory (*Carya* spp.) regeneration in oak-hickory forests of the southern Cumberland Plateau has not been widely studied. I assessed hickory regeneration under five silviculture prescriptions, including clear-cut harvests, three levels of shelterwood harvests, and no harvest. Each stand-level treatment was replicated three times and treatments were implemented from fall 2001 through winter 2002. Overstory composition was dominated by white oaks (*Quercus alba* L. and Q. *prinus* L.) (37 percent of the total basal area per acre, and 15 percent of the total stems per acre) followed by hickory (17 percent of the total basal area per acre, and 18 percent of the total stems per acre). Hickory regeneration of all size classes averaged 405 stems per acre across all stands pretreatment and 285 stems per acre four years post-treatment; the majority tallied were 1-foot tall or less than. Light and canopy cover differed among treatments and with time. After four years, hickory regeneration did not differ among treatments. There were no differences in survival among the five treatments for tagged hickory seedlings, and in 2006, hickory seedlings in the 25 percent retention treatment had the greatest height growth.

INTRODUCTION

For a variety of reasons, interest in regenerating the upland hardwood forests of the southern Cumberland Plateau has increased, as has the challenge of doing so. Upland forests in this region are aging, the effects of harvesting practices are unknown, and land ownership changes have altered planning goals. Although much research in upland hardwood forests, including those described as oak-hickory forest types, has focused on regeneration methods for the oak species (*Quercus* spp.), few studies have examined the ecology and silviculture of hickory (*Carya* spp.) (Hannah 1987, Johnson and others 2002, Loftis 1983b, Roach and Gingrich 1968, Sander 1977). There are many reasons to focus on regenerating hickory along with the other species typically found in upland hardwood forests (Fralish 2004). Recent attention has considered hickories as a key component in wildlife habitat, particularly for bats. Some bat species prefer roosting in the loosely attached bark of species such as shagbark hickory (*C. ovata* K.). It has long been reported that hickory nuts are valued by wildlife. Additionally, utilization and cultural trends in wood products have supported a rise in the market price of hickory lumber for cabinets and flooring (Luppold and others 2001). Maintaining the high flora and fauna biodiversity in these systems is also important.

Ascertaining how millions of oaks, hickories, yellow-poplar (*Liriodendron tulipifera* L.), and maples (*Acer* spp.) became established on medium to high productive sites remains a standard question considered when regenerating upland hardwood forests. Regenerating hardwood stands in similar systems has been documented in key studies by Loftis (1983a, 1983b, 1985, 1990), McGee (1967, 1975, 1979), McGee and Hooper (1970), Sander (1971, 1972), Sander and Clark (1971), Sander and others (1976). There has been much speculation on the conditions under which today's stands regenerated between 1820 and 1920 (Fralish 2004). Numerous studies have shown how site quality influences regeneration. Lower quality sites are found to be more easily regenerated to oak, and higher quality sites more difficult. Few studies have considered how site quality affects hickory regeneration.

Studies have shown that silviculture can be used to control factors such as light and spacing, which in turn greatly influence species response and stand composition. We also know some things about the probabilities for success using different types of regeneration on different sites. For example, for most species, stump sprouts are often more competitive than new seedlings. However, we know very little about the reproductive dynamics of hickory.

This study's main objective has been to quantify the sources and species composition of hickory regeneration resulting from a range of site disturbances. One goal is to help forest managers understand how stand manipulations will influence current stand dynamics and future composition and structure. Other ancillary goals are to help bring a positive financial return to the landowner and to maintain species diversity.

METHODS

Study Sites

To assess the shelterwood method of regenerating upland hardwood stands, I chose three sites on the mid-Cumberland Plateau in Jackson County, AL. The stands are located on strongly dissected margins and sides of the plateau (escarpment). On the escarpment study sites, soils are characterized as deep to very deep and loamy. They are considered well-drained, with moderate to moderately low soil fertility. Slopes range from 15 to 30 percent. Upland oak site index was 75 to 80, and yellow-poplar site index was 100 [base age 50 years, Smalley Landtype 16, Plateau escarpment and upper sandstone slopes and benches – north aspect (Smalley 1982)]. Canopies were dominated by oaks (*Quercus velutina* Lamarck, *Q. rubra* L., *Q. alba* L., *Q. prinus* L.), yellow-poplar, hickories, and sugar maple (*Acer saccharum* Marsh.), with a lesser proportion of ash (*Fraxnus* spp.) and blackgum (*Nyssa sylvatica* Marsh.). Depending on the site, dogwood (*Cornus florida* L.), sourwood (*Oxydendrum arboreum* DC.), Carolina buckthorn (*Rhamnus caroliniana* Walt.), and eastern redbud (*Cercis canadensis* L.) were common understory species. Beneath mature stands, oak reproduction was small and

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sparse, and competition by yellow-poplar and sugar maple was strong.

Treatments

Each site (block) comprised one replication of five treatments established along the slope contour. One replication, located on Miller Mountain (34˚58′30″N, 86˚12′30″W), had a southwestern aspect and a mean elevation of 1,600 feet. Two replications, located at Jack Gap (34˚56′30″N, 86˚04′00″W), had northern aspects. One Jack Gap replication was located at 1,500 feet elevation and the other at 1,200 feet. Treatments were randomly assigned to 10 acre areas within each replicated block. The treatments constituted five levels of overstory basal area retention: (1) 100 percent, untreated control; (2) 75 percent; (3) 50 percent; (4) 25 percent; and (5) 0 percent, clearcut. For the 50 and 25 percent retention, trees were marked to be retained using guidelines outlined by John Hodges, following those of Putnam and others (1960). Trees were chosen on the basis of species, favoring oak, ash and persimmon (*Diospyros virginiana* L.); and class, favoring preferred and reserve growing stock. All leave trees had dominant or codominant crown positions and exhibited high vigor. Trees were harvested by conventional methods using chainsaw felling and grapple skidding along predesignated trails. Roads were "daylighted" (trees on or adjacent to roads removed to allow sunlight in and surfaces to dry) and trees harvested from Fall 2001 through Winter 2002.

For the 75 percent retention treatment, an herbicide (Arsenal®, active ingredient imazapyr) was used to deaden the midstory. Rates of application were within the range recommended by the manufacturer. Watered solutions were made in the laboratory and then trees received application via waist-level hatchet wounds and a small, handheld sprayer. One incision was made per 3 inches diameter and each incision received approximately 0.15 fluid ounces of solution. Herbicide treatments were completed in Fall 2001, prior to leaf fall. The goal was to minimize the creation of overstory canopy gaps while removing 25 percent of basal area in the stand midstory. All injected trees were in lower canopy positions, reducing the creation of canopy gaps.

Measurements and Statistics

Prior to treatment, five measurement plots were systematically located in each treatment area. Plot centers were permanently marked with a 2 foot piece of reinforcing steel, and GPS coordinates were recorded. Regeneration was sampled on 0.01-acre circular plots. I tallied all vegetation in the regeneration plot. Seedlings were tallied by species by 1-foot height classes up to 4.5 feet tall; large seedlings were recorded as those greater than 4.5 feet tall up to 1.5 inches diameter at breast height (d.b.h.). Trees larger than 1.5 inches d.b.h. were tallied by diameter. Using the same plot center, a 0.025-acre plot was established and all trees 1.6 inches d.b.h. and greater were monumented (distance and azimuth measured and recorded from plot center, each tree tagged with a numbered aluminum tag) and species and d.b.h. recorded. An additional 0.2-acre plot, located concentrically, was established, and all trees 5.6 inches d.b.h. were measured and monumented as described previously.

In mid to late summer 2002, 2003, 2004, 2005, and 2006, all measurement plots were revisited. Regeneration was re-enumerated, and the status of all monumented trees recorded. A hand-held spherical densitometer was used to measure canopy cover above 4.5 feet, at plot center and at 12 feet in each cardinal direction from plot center. An AccuPAR Linear Par Ceptometer, Model PAR-80 (Decagon Devices, Inc, Pullman, WA, U.S.A.), was used to measure photosynthetically active radiation at each plot center and along transects equally dissecting each plot.

All data analyses were accomplished using the Statistical Analysis System (SAS Institute 1990). Analysis of variance was used to test for differences among treatments, and Duncan's Multiple Range test was used for mean comparisons ($p < 0.05$). Logistic regression was used to test the relationship among hickory sprouting probabilities and initial tree diameters.

RESULTS

Overstory Tree Conditions

Treatments resulted in a gradient of residual stand conditions, following 105.9 square feet per acre for the control, 82.1 square feet per acre for the 75 percent treatment, 40.2 square feet per acre for the 50 percent treatment, 27.3 square feet per acre for the 25 percent treatment and 5.1 square feet per acre for the clearcut. The 50 and 25 percent treatments were not significantly different from one another. Hickory species tallied in all stands included pignut, red, shagbark, and mockernut (*Carya glabra* Sweet, *C. ovalis* Sarg., *C. ovata* K. Koch, and *C. tomentosa* Nutt.). Hickory species were combined for all analysis. Following treatment, hickory basal area was 4, 15, 11, 2, and 1 percent of the total basal for control, 75 percent, 50 percent, 25 percent and clearcut stands. Overstory hickory stems per acre remained unchanged from pretreatment values through 2006 for the control (15 stems per acre (SPA)) and the 75 percent retention treatment (24 SPA). There was less than one SPA of hickory remaining after clearcutting. In the 50 percent retention treatment, hickory SPA in the overstory went from 24 to 3, and in the 25 percent treatment they declined from 16 to 1 SPA.

Canopy Cover

Densiometer data were significantly different among treatments for each post-treatment year measured (table 1). The control and 75 percent retention treatments did not differ in their percent cover. The 75-percent retention treatment was aimed at reducing the midstory, without altering the main canopy, so this result was expected. Both of these treatments had significantly greater canopy cover compared to the other three treatments for years 2002, 2003, and 2004; in those same years, the 50 and 25 percent retention treatments were not significantly different from one another but were from the other three treatments, and the clearcut was significantly different from the other four treatments. In 2005 and 2006, the 50 percent retention treatment had similar canopy cover as the 75 percent treatment. The high productive nature of these systems caused the vegetation to respond quickly to increased space and light. By 2006, percent canopy cover of

Table 1—Canopy cover percentages for each treatment by year

	2002	2003	2004	2005	2006
Control	99.7a	96.8a	98.9a	96.2a	95.8a
Seventy-five	98.3a	94.6a	92.6a	92.3ab	91.9ab
Fifty	76.0b	48.0b	71.9b	87.8bc	84.2bc
Twenty-five	74.9b	44.7b	65.1b	82.0c	85.2c
Clearcut	31.0c	25.4c	47.6c	80.4c	83.7c

Values in columns with the same letters are not significantly different.

the three harvested treatments (50, 25, and clearcut) were not significantly different from one another.

Understory Light Levels

There were significant differences in the reduction of full sunlight reaching the understory each year post-treatment (table 2). In all five measurements post-treatment, the control plots had significantly greater reductions in full sunlight reaching the forest floor than did the other five treatments. In 2004, the control and 75 percent retention treatments did not differ from one another, but were significantly different from the other three treatments. After five growing seasons, four distinct light regimes were measured below the canopy, and the greatest reduction in light was under the control treatments, followed by the 75 percent retention treatment and then the 50 percent retention treatment. In 2006 there was no difference in light reduction under the 25 percent retention treatment and the clearcut, although these treatments both differed from the other three.

Seedlings Counts

Seedling counts for natural regeneration in the 75 percent retention treatment showed that for all species, the total number of seedlings in all height classes changed from 9,439 SPA in 2001 (pretreatment) to 7,768 SPA in 2006 (post-treatment) (table 3). However, it is noteworthy that these

Table 2—Light reduction percentages for each treatment by year

	2002	2003	2004	2005	2006
Control	92a	94a	97a	96a	98a
	(10.3)	(7.7)	(4.9)	(6.6)	(1.6)
Seventy-five	83b	83b	94a	92b	91b
	(13.9)	(16.1)	(7.2)	(11.8)	(4.1)
Fifty	66c	68c	73b	82d	83c
	(32.0)	(21.7)	(20.7)	(22.4)	(7.3)
Twenty-five	69c	47d	75b	86c	67d
	(25.5)	(29.8)	(19.2)	(16.4)	(22.1)
Clearcut	41d	41e	41c	63e	67d
	(21.4)	(21.4)	(23.4)	(27.2)	(18.1)

Values in columns with the same letters are not significantly different; numbers in parentheses are one standard deviation.

Table 3—Seedling counts per acre for natural regeneration of all species encountered and for all hickory species

	< 1 ft		1 to 4.5 ft		> 4.5 ft		Total	
	All	Hic	All	Hic	All	Hic	All	Hic
Control 2001	5284	365	2771	50	185	15	8240	430
Control 2006	2271	350	2698	39	286	34	5255	423
Seventy-five 2001	7040	333	2171	29	228	22	9439	384
Seventy-five 2006	3584	295	4084	29	100	24	7768	348
Fifty 2001	4670	253	3498	82	300	18	8468	353
Fifty 2006	857	78	5941	266	243	0	7041	344
Twenty-five 2001	5426	326	4370	136	243	16	10039	478
Twenty-five 2006	1428	78	6040	339	215	0	7683	417
Clearcut 2001	5998	287	3270	38	257	19	9525	344
Clearcut 2006	828	107	5469	189	144	0	6441	296

totals are not absolute because counts in the 0.01-acre plot of more than 25 for a given species in a given height class were recorded as 25, and not truly enumerated. Hickory seedling tallies in this treatment were 384 SPA in 2001, and 348 SPA in 2006. Control SPA for all species decreased from 8,240 to 5,255 SPA, and the hickory component remained relatively unchanged, with 430 SPA in 2001 and 423 in 2006. Totals by height classes did not differ between years for the control and 75 percent retention treatments. In the 50, 25, and clearcut treatments, the number of hickory stems that were 1.0 to 4.5 feet tall increased from 2001 to 2006: 82 to 266, 136 to 339, and 38 to 189 SPA, respectively. The number of SPA greater than 4.5 feet tall decreased to zero in all three of these treatments.

Tagged Hickory Seedling Survival and Growth

There were no significant differences in percent survival among the five treatments for the hickory seedlings that were tagged and followed, for each year measurements were made (fig. 1).

There were 20 tagged hickory seedlings in the 50, 75 percent, and clearcut treatments, 28 tagged seedlings in the control, and 16 in the 25 percent retention treatment. Relative height and basal diameter growth of the tagged hickory seedlings differed among treatments only for relative height growth in 2006. In 2006, relative height growth of the seedlings in the 25 percent retention treatment was significantly greater than height growth in the control. In 2006, the relative height growth of seedlings in each treatment was 1.6 inches for the control, 5.1 inches for seedlings in the 75 percent retention, 8.7 inches for the clearcut treatment, 11.4 inches for 50 percent retention, and 18.9 inches for the 25 percent retention treatment (fig. 2). Relative diameter growth was negligible and not significantly different among the treatments.

Hickory Sprouting Probabilities

Across the three harvest treatments (50 and 25 percent retentions and clearcut), 158 total sample hickory trees were tallied (1.5 inches d.b.h. and greater). From each cut hickory

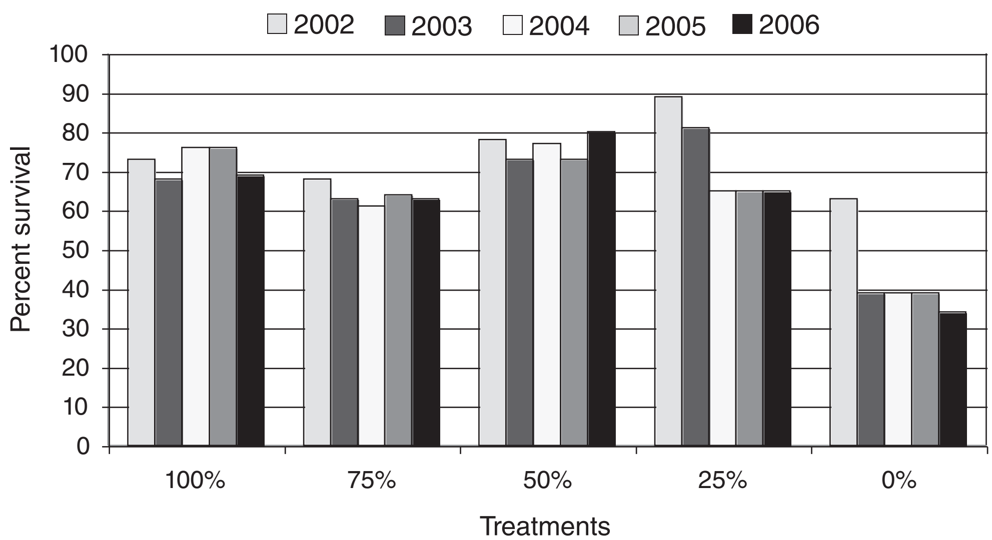

Figure 1—Tagged hickory seedling survival percentages compared among treatments by year. No significant differences were found.

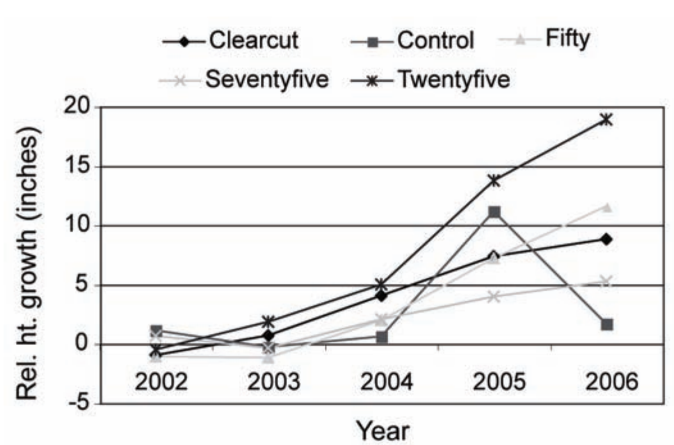

Figure 2—Relative height growth of tagged hickory seedlings in all treatments over 5 years.

tree, I recorded whether each had sprouted or not, and I used these data in logistic regression analysis to estimate the probability of sprouting as related to initial tree d.b.h. For cut trees, hickory sprouting probability decreased with increasing initial tree diameter (fig. 3). Logistic regression (binary outcome, sprout or no sprout) likelihood ratio indicated significance at $p<0.0025$.

DISCUSSION

For analysis of this study I combined the four hickory species tallied into one group; there was no dominant hickory species. Prior to stand manipulations, hickories on these sites averaged 13 SPA and comprised 11 percent of the total basal area. Overstory hickory species were not favored as residual trees, and very few remained after harvesting.

Treatments created a gradient of light levels. Species that adapt rapidly to their environment may have a competitive advantage in habitats with changing light intensities. Little is known about how hickory regenerates or how it may respond to changing light, although in this study, hickory showed minimal response to increased light. However, because these systems respond rapidly to disturbance, residual trees may be influencing reproduction within a few years following disturbance. The difference in light levels dissipated with time; the greater-cut treatments reduced light by almost 70 percent after five growing seasons. Miller and others (2006) found that reserve trees in a two-aged system rapidly expanded their crowns and influenced the composition of reproduction.

This study explored ways to regenerate these stands and maintain a known hickory component by manipulating overstory and midstory stand structure to alter light and growing conditions. In a previous study, Schweitzer and others (2004) used a multispecies regeneration model to compare predicted species composition with regeneration goals. The predictions from this model are for stand composition following an extensive regeneration cut. Model predictions for these stands enumerated 462 SPA at crown closure following treatment, with 27 percent black cherry (*Prunus serotina* Ehrh.), 21 percent black locust (*Robinia pseudoacacia* L.), 15 percent sugar maple, and 12 percent yellow-poplar. Hickory was predicted to comprise only 2 percent of the total SPA. The model does not predict how species compete under shelterwood conditions, such as those created in this study. However, study data will contribute to calibrate the model to predict species composition under different regeneration regimes.

In my seedling tallies, there was little recruitment of hickory into the largest size class following disturbance. Reducing just the midstory did not appear to favor hickory recruitment of any size class, nor hickory seedling growth. The three treatments that altered the light environment the most, the clearcut, 50 and 25 percent retention treatments, all had an increase in the number of seedlings tallied in the 'greater than 1 foot tall but less than 4.5 feet tall' class. These three treatments also produced no seedlings in the largest seedling size class. The disturbance was, in fact, detrimental to these larger seedlings. Mann (1984) reported that mechanical damage to stumps and soil incurred during harvesting treatments influenced seedling abundance. After five growing seasons, tagged hickory seedlings changed little in their relative growth; only seedlings in the 25 percent retention treatment were significantly taller than those in the controls. Although the vegetation has responded quickly under favorable site conditions, more time will be needed to make a definitive assessment of the response of hickory regeneration.

Stump sprouts may provide for some hickory recruitment into the next stand. At 10 inches d.b.h., there was approximately a 50 percent chance of the hickory sprouting from the stump after harvest. On average there were 13 SPA of hickory less than or equal to 10 inches d.b.h. Additional analysis incorporating the vigor of the sprouts, as well as edaphic and topographic features of the sites to strengthen the probability predictions is warranted.

CONCLUSIONS

Naturally regenerating the suite of hardwood species on any given site can be complicated. Much research has focused on regenerating oak on better quality sites, and little attention has been given to species such as hickory.

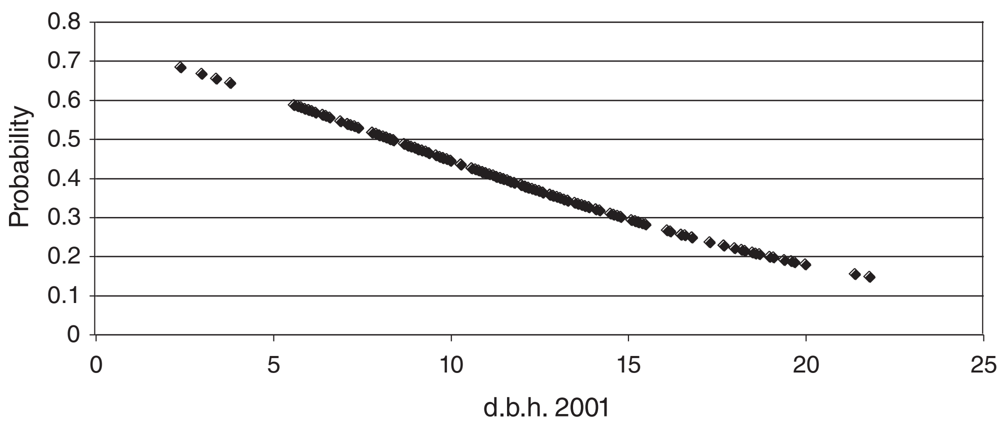

Figure 3—Hickory sprouting probabilities for cut trees on the 25- and 50-percent retention treatments and clearcuts.

Some have suggested that hickory is playing a major role in the replacement of American chestnut (*Castanea dentata* Mill.) and could be considered a inter-generational species (Johnson and Ware 1982). With the recent increased interest in biodiversity and conservation in the forested systems of the Cumberland Plateau, we need to direct our attention to manipulating stands, in order to obtain and retain myriad species composition. Our knowledge base for doing so is limited, but we can use methods for similar species and incorporate the response of all species. Thus far, regenerating hickory using silvicultural prescriptions successful in regenerating oak, such as the midstory reduction treatments, has not resulted in the recruitment or growth of hickory seedlings.

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ACCELERATING DEVELOPMENT WITH FERTILIZATION IN A YOUNG NATURAL PIEDMONT MIXED HARDWOOD PINE STAND

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Abstract—A rising two-year-old even-aged naturally regenerated upland Piedmont mixed hardwood-pine stand was broadcast fertilized with N, N + P, and N + P + K to evaluate stand level responses to fertility treatments. There were significant positive stand responses in self thinning and mean stem size measured two growing seasons after fertilizer applications. Findings suggest efficient ways to enhance productivity with implications for age at final age harvest and economic value.

INTRODUCTION

Very many acres across eastern North America are managed (or perhaps best managed) as naturally-regenerated even-aged mixed-species stands, with growth rates not as fast as desired. A central question for foresters managing these stands for commodity production is: Can these growth rates be accelerated? In addition, very many acres of these stands are not managed at all, or not between the time of regeneration and when they reach pole-size. The relevant question in this regard is: Can young stands, ages 1 to 15, be managed efficiently to enhance growth rate?

In the current study we sought to evaluate the impact of broadcast fertilization of N, N+P, and N+P+K on the growth of a rising two-year-old naturally regenerated mixed species upland Piedmont stand in NC. A number of other researchers have addressed similar questions in natural hardwoods, with a wide variety of results (Auchmoody 1989, Beckjord and others 1983, Dunn and others 1999, Graney and Pope 1978, Johnson and others 1997, Lamson 1978, Newton and others 2001).

METHODS

The study was conducted in central NC on an upland mixed-species Piedmont site (site index 23 m for loblolly pine at 50 years) on the NC State University Hill Demonstration Forest in Durham County (Kirby 1976). The site has previously been occupied by a maturing 33-year-old loblolly pine plantation with a large component of mixed hardwood understory and some hardwood overstory. That stand was salvage clearcut in early 2003 following severe ice storm damage. All trees greater than 4 cm d.b.h. were either cut during the harvest, or girdled before the installation of the current study.

Across the site 4 blocked replications of 20.4 by 10.2 m plots were delineated in rising 2-year-old natural regeneration in May 2004. Each replication included four treatments of hand broadcast fertilizer (table 1).

An initial inventory of stems was conducted in June 2004 (one month after the fertilizer treatments were applied) whereby a single 2-m wide transect through the middle of the plot was delineated and the height of each stem to the 2003 growth cessation point was recorded for all stems greater than 60 cm tall. No significant differences in stem density or height were found among treatment plots or blocks. In October 2005, two growing seasons after fertilizer treatment a second inventory was conducted. This time two 2-m wide transects per plot were delineated and stem height and ground-line diameter (GLD) for stems over 60 cm tall were recorded.

The most common species on the site were 29 percent loblolly pine (*Pinus taeda*), 16 percent sweetgum (*Liquidambar styraciflua*), 13 percent red maple (*Acer rubrum*), 12 percent red oak group (*Quercus* spp.), 10 percent tulip poplar (*Liriodendron tulipifera*), 6 percent hickory (*Carya* spp.), and 5 percent white oak group (*Quercus* spp.).

RESULTS AND DISCUSSION

There were significant differences among fertilizer treatments plots in mean stem height, groundline diameter (GDL), and a volume index of GLD*GLD*height (table 2).

On this site there were significant growth responses to the treatments, generally with Control < N < N + P = N + P + K for groundline diameter, height and volume index. While there were no significant differences among treatments with

Table 1—Fertilizer treatments applied to rising 2-year-old natural mixed hardwood-pine regeneration on the Hill Forest, Durham County, NC

Treatments	Kg of N/ha	Kg of P/ha	Kg of K/ha
Control	0	0	0
N	200	0	0
N+P	200	50	0
N+P+K	200	50	100

Note: N applied as ammonium nitrate (34-0-0), P applied as triple super phosphate (0-46-0), K applied as potash (0-0-60).

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Table 2—Two year whole stand all species combined growth response to fertilizer treatments as measured on naturally regenerated 3-year-old mixed hardwood-pine stems on the Hill Forest, Durham County, NC

Measurement	- - - - - - Fertilizer Treatments - - - - - - -				Level of ANOVA
Parameter	Control	N only	N + P	N + P + K	Significance
Density (Number per ha)	52,000	39,000	35,000	37,000	ns
Groundline Diameter (GLD) (cm)	1.4	1.7	2.1	1.9	P<0.05
Height (Ht) (cm)	128	173	212	177	P<0.05
Volume Index (GLD*GLD*Ht)	65	108	169	147	P<0.05

respect to stem density after two years, there was a strong trend to suggest that the accelerated growth of stems under any of the fertilizer treatment regimes had promoted self thinning and a reduction in stem density (table 2).

These findings indicate that on relatively low fertility Piedmont sites that the growth of natural regeneration can be greatly enhanced by modest fertilizer applications. The N and P fertilizer rates used in this study are similar to those used to promote the growth of planted pines in the region. The use of K fertilizer in the current study was exploratory, given some indication in other studies that sweetgum might responds favorably to K addition (Coleman and others 2003). While in the current analysis it can not be determined how sweetgum specifically responded to K, it is evident that overall stand response was similar between the N + P and N + P + K plots. There is some unexplained indication that the addition inclusion of K with N and P reduced the growth response relative to N + P only.

Fertilizer application to planted pine forests in the U.S. south has become fairly routine (Albaugh and others 1984), and could be readily expanded to naturally regenerated mixed species stands, on sites justifying the intervention. Stand response at very young ages, as measured in the current study, may serve to promote stand development through self thinning, and the concentration of growth on fewer stems. These processes could lead to reduced rotation age, and perhaps enhanced species composition if differential species response could be targeted, and thereby enhance economic returns (Siry and others 2004). Very young stands in similar conditions have also responded positively to the effects of thinning and herbaceous competition control (Romagosa and Robison 2003, Newton and others 2001, Schuler and Robison 2006), and together with fertilization there may practical ways to promote the development and value of these stands.

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Hardwood Natural Regeneration

Moderator:

NANCY HERBERT

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CERULEAN WARBLER RESPONSE TO SILVICULTURAL MANIPULATIONS ON MANAGED FORESTLAND IN DESHA CO., ARKANSAS, THIRD YEAR RESULTS

Paul B. Hamel, Mike Staten, Rodney Wishard, and Carl G. Smith, III[1]

Abstract—Cerulean Warbler is a Nearctic-Neotropical migratory bird in need of management attention for which only rudiments of a silvicultural prescription exist. Since 1992, we have monitored breeding populations of this and other canopy-dwelling warbler species on a 54-ha site in Desha County, AR, owned and managed by Anderson-Tully Co. for production of high quality sawtimber. We instituted an experiment in 2002 to assess the response of this species to alternative silvicultural treatments. We split the site in two plots of equal area and with similar histories of use by Cerulean Warblers, and we randomly assigned one of two prescriptions to each plot. The treatments were 1) a standard Company prescription designed to favor development of sawtimber trees and 2) a "Cerulean Warbler prescription" (CWP), designed to favor development of large sawtimber trees for use as song perches by male Cerulean Warblers and large shade-tolerant trees in the midstory as potential Cerulean Warbler nest trees. Harvesting was completed in winter 2004. Survey of Cerulean Warbler response in 2006 indicated that the birds have begun breeding on portions of the CWP plot. At least three males, two of whom attracted females, established and defended territories on and adjacent to the CWP plot.

INTRODUCTION

Applying a silvicultural prescription that produces habitat for a wildlife species of concern is one important way to incorporate nontimber values into management of forest lands. Using such a prescription, a silviculturist can conduct specific interventions in the forest with a clear understanding of their outcomes. Wildlife species of conservation concern are increasingly the primary objectives in certain forest management situations.

Cerulean Warbler is a small, insectivorous, Nearctic-Neotropical migratory songbird (Hamel 2000b). The species is of considerable conservation concern (Birdlife International 2004, 2006, COSEWIC 2003) because of population declines registered since 1966 at approximately 3 percent per year (Link and Sauer 2002, Jones and others 2004). Because of declines and a recognition that habitat loss is the primary causal factor, the species recently was evaluated for inclusion on the list of threatened and endangered species (U.S. Fish and Wildlife Service 2006). Current population levels indicate that such listing is not now warranted (U.S. Fish and Wildlife Service 2006), but no specific mechanism to reverse the declines has been demonstrated (Buehler and others 2008). These birds are the focus of an international effort, which is known as the Cerulean Warbler Technical Group, to develop a management strategy that produces habitats and enhances populations while integrating these goals into normal economic activity (Hamel and others 2004). The species is universally recognized as occupants of mature hardwood stands, and as preferentially using large sawtimber trees for nesting purposes and singing. Male and female Cerulean Warblers use the forest in slightly different ways, however, such that males are relatively more dependent upon large, shade intolerant canopy trees for singing, and females are relatively more dependent upon use of moderate-sized midstory trees of more shade tolerant species for nesting (Barg and others 2006, Hamel 2003, Hamel 2006, Hamel and Rosenberg 2007).

Since 1992, we have been studying a population of Cerulean Warblers on managed forest land in Desha County, AR. Our work allowed us to characterize Cerulean Warbler use of tree species, crown class, and shade tolerance of canopy trees, features of structure and composition amenable to manipulation through silvicultural means. We used this pretreatment work to develop an alternative prescription designed to improve habitat for Cerulean Warbler and to compare it with a standard prescription on the same study site (Hamel and others 2006). In this paper we report on response of the birds to treatments after three growing seasons.

METHODS

Study Site

Our study area was a 54.5 ha site (33° 44' N, 91° 9' W, hereafter Study Grid) on the Desha Delta Hunt Club in Desha County, in southeastern AR (Hamel 1998, Hamel and others 2006, Woodson and others 1995). The site is part of a 130-ha compartment (hereafter Treatment Area) within a larger, contiguous ownership of Anderson-Tully Co., which manages it for production of high quality sawtimber. It is located in the Mississippi Alluvial Valley, in the batture land of the Mississippi River, on sandy loam soil with ridge and swale topography near the River's bank. The site is typical of riverfront hardwood ecosystems in the Lower Mississippi Valley. Prior to our study, in 1991, a harvest treatment according to standard Company prescription (SCP) was conducted within the compartment. In that year, Staten and colleagues located Cerulean Warblers on the tract as part of another study (Hamel 1998, Hamel and others 1998). Pretreatment sampling (Hamel and others 1998, Hamel and others 2006) included marking the area at the intersections of a 50 by 50 m grid (N = 230 intersections). In 2002, the Treatment Area was scheduled for entry in the normal rotation on Company lands. We used this opportunity to implement an unreplicated experiment to assess response of the species to alternative silvicultural treatments. Harvesting

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was done by partial cutting during the nonbreeding period for Cerulean Warblers; it began in winter 2002 and was completed in winter 2004. We subdivided the Study Grid into north and south subplots. By coin flip, the north subplot was selected to receive the CWP, and the south subplot received the SCP.

Silvicultural Treatments

Standard prescription—The SCP applied to the southern plot, including the southern half of the Study Grid, was a partial cutting prescription with elements of improvement cutting, thinning, and regeneration cutting. It involved cutting in the overstory to reduce mortality, improve species composition and spacing, and increase growth of the residual stand. It further involved cutting in the midstory to remove poorly formed shade tolerant species in order to release advance regeneration and encourage the establishment and growth of additional shade intolerant regeneration of desirable species. The prescription was implemented by marking stems to be removed in the stand. Other stems, including all elm (*Ulmus americana* L.), sugarberry (*Celtis laevigata* L.) and boxelder (*Acer negundo* L.) stems, were cut unless they were of superior form and quality. The SCP and initial effects of its application to the southern plot are documented in Hamel and others (2006).

Cerulean Warbler prescription—Applied to the northern half of the Treatment Area and Study Grid, the CWP was developed based on findings of Hamel (2003). This prescription recognized the importance of tall sawtimber trees as song perch trees of male Cerulean Warblers, and that large, often shade tolerant, trees can be important for nest trees. This partial cutting prescription was a modification of the SCP, involving elements of improvement cutting, thinning, and regeneration cutting. The CWP differed from the SCP in that fewer trees were removed from the shade tolerant midstory. Before timber marking began, researchers and foresters trained together on identification of shade tolerant midstory trees desirable for potential nest trees. Such potential nest trees were specially indicated by painting an "X" on them and they were excluded from the timber harvest. The CWP and initial effects of its application within the northern subplot are documented in Hamel and others (2006).

Post-harvest monitoring

Vegetation sampling—Samples of vegetation have been measured on the Study Grid in 1993, 2002, 2005, and 2007. We here summarize results of the 2007 sampling session and make brief comparisons to those made in 2005 and earlier. Detailed comparison of the pretreatment (1993 and 2002) and initial post-treatment samples (2005) are available in Hamel and others (2006). In 2007, we randomly selected 30 grid intersection points in both the SCP and CWP subplots. Gridpoints sampled in 2005 were not resampled in 2007. At each point, canopy trees were selected for inclusion in the sample using a 30 BAF English (6.9 BAF metric) angle gauge. Each selected tree was identified to species and its height measured in m, diameter at breast height measured in cm, crown class determined, and presence of vines in its canopy noted. We further recorded the distance and azimuth from gridpoint to each tree. We randomly selected ten locations at which Cerulean Warblers were observed and made identical vegetation measurements at each of them.

Cerulean Warbler sampling—A map of territories (spotmap census) of Cerulean Warbler and other warbler species present on the Study Grid (Bibby and others 1992) was conducted in 2006 as in 2004 and annual pretreatment surveys. Biennial spotmap censuses are anticipated in the future. Singing Cerulean Warblers were located and the locations marked using GPS devices.

Data analysis

We tested the hypothesis that no differences existed in basal area and density of trees and saplings on the two subplots after three growing seasons using analysis of variance. We used the techniques of Goelz (1995) to determine stocking on the subplots and compared those to each other, and to use by Cerulean Warbler, using analysis of variance. Distribution of observed Cerulean Warbler territories on the Study Grid in pretreatment surveys 1992 through 2001 was visually compared to the first sample post-treatment (2004) and current (2006) map. Statistical tests were carried out using SAS (SAS Institute 1999-2000) with statistical significance accepted at P = 0.05. Where sample sizes were too small to possess sufficient power to conduct rigorous statistical comparisons, we present graphical results without further comment in this progress report.

RESULTS AND DISCUSSION

During pretreatment surveys, 1992 through 2001, Cerulean Warbler territories were widely distributed throughout the Study Grid. In 2004, three Cerulean Warbler territories were located at the extreme northern edge of the CWP subplot. In 2006, as in 2004, a small number of singing male Cerulean Warblers established territories at the northern edge of the CWP subplot of the Study Grid, but entirely within the area treated by the CWP (fig. 1). In 2006, unlike 2004 (Hamel and others 2006), we repeatedly observed female Cerulean Warblers using the CWP subplot, in association with two of the singing male territories. However, we did not find a nest. As in 2004, no Cerulean Warbler use was detected in the SCP subplot. Even more than in 2004, Cerulean Warbler use in 2006 was concentrated in areas in which no territories were observed in the pretreatment period.

Vegetation measurements taken in 2007, unlike those sampled in 2005 (Hamel and others 2006), did not differ between CWP and SCP subplots (table 1, Tree Density: $F_{1, 59} = 0.15$, P = 0.70, $R^2 = 0.002$; Tree Basal Area: $F_{1, 59} = 3.90$, P = 0.05, $R^2 = 0.06$). We believe this reflects the limited sample size we were able to achieve for this report rather than a lack of difference. We illustrate our opinion graphically using the stocking data. Stocking levels for both treatments are demonstrated to be lower than those in the pretreatment samples (fig. 2). However, comparison of random samples from 2005 and 2007 produced conflicting results. While both samples yielded stocking levels lower than those in the pretreatment samples, the results are not internally consistent. Our 2007 samples are too small for adequate power to detect differences between the CWP and SCP subplots. For this reason we pooled stocking values for gridpoints sampled 2005 with those for gridpoints sampled

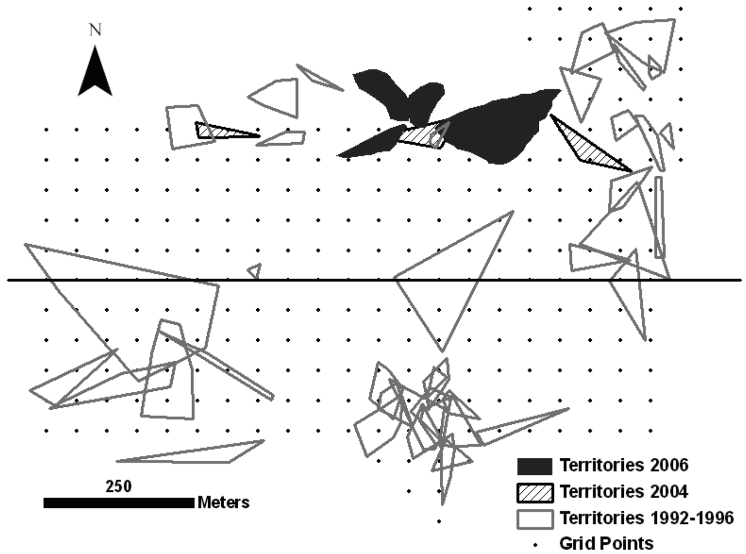

Figure 1—Distribution of Cerulean Warbler territories on Desha Delta Hunt Club Cerulean Warbler Study Grid, Desha Co., AR. Dark horizontal line indicates boundary between Cerulean Warbler prescription area to the North, and Standard company prescription area to the South.

2007 and present the results as single values for each of the treatments (fig. 2).

Stocking levels of 2007 plots made in Cerulean Warbler territories were comparable to those from plots made around Cerulean Warbler nests in the pretreatment sample, indicating a greater consistency in Cerulean Warbler use of the Study Grid pre- vs post-treatment than in different samples taken at random from portions of the area treated by either prescription. Stocking levels for nests in the pretreatment sample and for Cerulean Warbler territories in the 2007 post-treatment sample are both within the range suggested by Kahl and others (1985; 65 to 85 percent) as indicative of good Cerulean Warbler habitat in Missouri uplands.

CONCLUSIONS

To date, our results suggest that silvicultural treatments such as our CWP can produce breeding habitat for this species. Stand stocking may be a useful measure for describing and comparing Cerulean Warbler habitat. Our short-term goals for this experiment are to: (1) evaluate regeneration in 2009 after five growing seasons; (2) increase vegetation sampling effort in future monitoring activities; (3) find Cerulean Warbler

Table 1—Tree density and basal area on Desha Delta Hunt Club Cerulean Warbler study grid, pre- and post-treatment. Values for Cerulean Warbler prescription area and Standard company prescription area show samples measured at all (pretreatment) or randomly selected (2005, 2007) intersection points of the Study Grid. Values for Cerulean Warbler use reflect points centered under nests or song perches as indicated. Values reflect mean ±1 S.E.

Treatment area	Pretreatment	2005	2007
Cerulean Warbler prescription area	N=137	N=26	N=30
Basal area, sq. ft. per acre	138.3 ± 5.1	120 ± 12.2	103 ± 10.2
Trees per acre	170.3 ± 11.2	56 ± 5.4	159.7 ± 21.1
Standard company prescription area	N=123	N=26	N=30
Basal area, sq. ft. per acre	118.4 ± 5.1	64.6 ± 9.1	76 ± 9.1
Trees per acre	141 ± 9.3	64.6 ± 17.7	173.9 ± 29.3
Cerulean Warbler use	N=18 nests	-	N=10 song perches
Basal area, sq. ft. per acre	100 ± 10.2	-	96 ± 8.7
Trees per acre	132.7 ± 9.5	-	102.2 ± 14.7

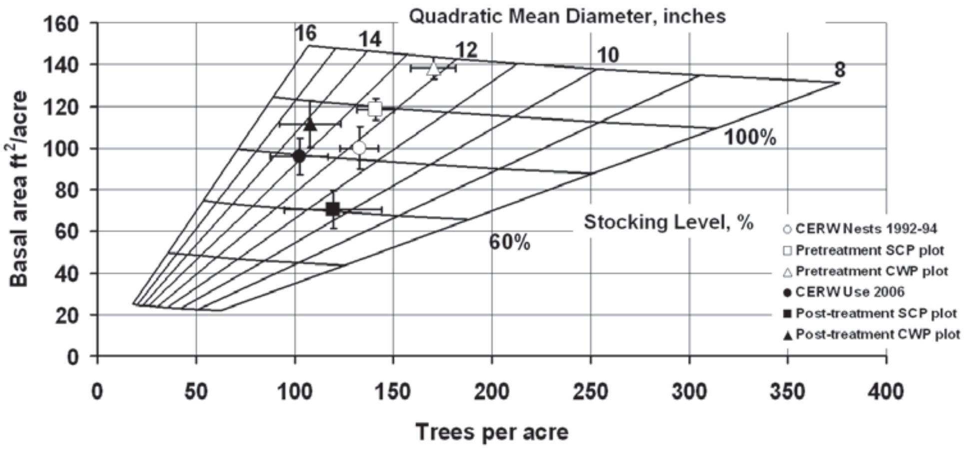

Figure 2—Density and basal area of trees measured on plots in Desha Delta Hunt Club Cerulean Warbler Study Grid, depicted on stocking chart of Goelz (1995). Open symbols refer to pretreatment conditions; closed symbols indicate pooled results of post-treatment sampling 2005 and 2007. Error bars indicate 1 S.E. about the mean values which are plotted. Triangles indicate Cerulean Warbler prescription area, squares indicate Standard company prescription area, and circles indicate Cerulean Warbler use.

nests; and (4) estimate economic difference between the treatments and thereby to evaluate relative cost of the CWP and the SCP.

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ABUNDANCE AND POPULATION STRUCTURE OF EASTERN WORM SNAKES IN FOREST STANDS WITH VAROUS LEVELS OF OVERSTORY TREE RETENTION

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Abstract—In-depth analyses of a species' response to canopy retention treatments can provide insight into reasons for observed changes in abundance. The eastern worm snake (*Carphophis amoenus amoenus* Say) is common in many eastern deciduous forests, yet little is known about the ecology of the species in managed forests. We examined the relationship between silvicultural techniques, particularly shelterwood cuts with varying levels of basal area retention, and the abundance and population structure of eastern worm snakes in the Cumberland Plateau of northern Alabama. Treatments included five levels of basal area retention at 15 units (4 ha/unit): 0, 25, 50, 75 percent retention, and control (100 percent retention) with three replicates each. Drift fences and coverboards were used to sample worm snake populations in each treatment. Worm snake abundance did not vary among treatments. Sex ratios were skewed towards males on clearcut treatments. The percentage of females in gravid condition did not differ among treatments, and the percentage of the sample comprised of juveniles was consistently high and also did not vary among treatments. Male worm snakes were more massive at a given length in controls than 25 percent retention treatments. Mass to length ratio increased linearly with increasing basal area for males. Our results highlight the subtle changes that these treatments exerted on eastern worm snakes.

INTRODUCTION

The eastern worm snake (*Carphophis ameonus. amoenus* Say) is a secretive, small (< 30 cm total length), fossorial snake that is distributed from southern NY and MA south to northern AL, GA, and SC (Conant and Collins 1991). In AL the species inhabits a variety of habitats, and is a common forest floor inhabitant of mesophytic forests (Mount 1975). Although the species can reach high densities relative to other reptile species in optimal habitat (Ernst and Barbour 1989), there are few detailed ecological studies of the species, especially on the effects of canopy removal. Work by Russell and Hanlin (1999) showed that this species reaches high abundances adjacent to small isolated wetlands in the Coastal Plain of SC. In KY, the species was studied using radioisotope tags and found to have small home ranges (23 to 486 m^2) (Barbour and others 1969).

The objectives of this study were to compare the abundance, demographics, population structure, and body size of eastern worm snakes across five levels of overstory tree retention in northern AL. In doing so we tested the following four hypotheses:

$H1_o$: Relative abundance of worm snakes will not vary by canopy retention treatment
$H2_o$: Sex ratio, percentage of population comprised of gravid females and juveniles will not vary by treatment
$H3_o$: Body size distribution will not vary by treatment
$H4_o$: Ratio of mass: length will not vary by treatment

STUDY AREA

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

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

METHODS

Stand Density

Basal area was calculated using diameter at breast height measurements taken in three permanent measurement plots within each experimental unit (Schweitzer 2003) in each year between 2002 and 2005.

Snake Sampling

The main method used to sample worm snakes was drift fence trapping. Drift fences were 15 m in length, constructed of silt fencing, and included one 19 liter pitfall bucket at each end, and two double-sided funnel traps placed on either side of fences at the midpoint. Three drift fences were placed on each unit (nine per treatment, 45 total) adjacent to the same permanent measurement plots used to measure stand density. Drift fences were opened for a total of 900 trap nights during the following periods: August to October 2002 and March to October 2003, 2004, and 2005. A trap night was defined as one drift fence open for 24 hours. Drift fences were checked daily when opened. Artificial cover objects, or coverboards, were also used for snake sampling. Two coverboard types were deployed on treatments and sampled

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up to 3 to 4 times per week between April and July of 2003 to 2005 and up to once weekly between October and March of the same years. Ninety small coverboards (30 by 20 cm), 30 at each measurement plot, were placed within each unit and sampled a total of 46 times (62 100 boards), while 9 larger (120 by 60 cm) boards, three per measurement plot, were used per plot and sampled 73 times (9 855 boards). Each captured worm snake was measured for snout-vent length (SVL) using a Lufkin steel pocket tape, weighed to the nearest 0.1 g with Pesola spring scales, probed to determine sex, and given a dorsal scale clip. Gravidity of females was assessed based on the presence of eggs which are visible within the body cavity.

Statistical Analyses

Randomized complete block ANOVA tests were used for comparison of worm snake abundance among treatments in terms of effort-adjusted drift fence and cover board captures. The same ANOVA model was used to test for treatment effect on log-transformed mass: length ratio of male and female worm snakes to determine if treatments affected body size relationships. Mean separations were performed using Tukey's HSD test. To test for differences in sex ratio, percentage of gravid females, or percentage of juveniles among the five tree retention levels we used χ^2. Simple linear regression was utilized to test for relationships between log-transformed mass to length ratio of individual male and female worm snakes and the average basal area (2002 to 2005) at the measurement plot at which they were captured. Population structure patterns among treatments were assessed graphically using a histogram of snake sizes. Data from each of the three measurement plots within a given unit were averaged for all analyses except regression of mass: length ratio and basal area. Analyses were carried out using SPSS V. 10.0 and $P < 0.05$ for significance.

RESULTS

A total of 206 individual eastern worm snakes were captured, excluding 35 recaptures. This total included 127 snakes captured with coverboards and 79 captured with drift fences. Ninety of these were juveniles (< 165 mm SVL; Russell and Hanlin 1999) whereas 116 were classified as adults. The sample included 44 males and 56 females, 17 which were gravid.

Relative Abundance

Worm snake abundance did not differ by treatment in terms of either drift fence ($F_{4,10} = 0.37$, $P = 0.82$) or coverboard ($F_{4,10} = 2.01$, $P = 0.17$) captures (fig. 1 a, b). Because the two sampling techniques showed similar patterns of abundance among treatments, drift fence and coverboard captures were combined for other analyses.

Demographics

Sex ratios differed among treatments ($\chi^2 = 15.43$, $P >$ 0.01) and ratios were skewed towards males on clearcut treatments (fig. 2). The percentage of females that were gravid did not differ among treatments ($\chi^2 = 5.46$, $P = 0.2$).

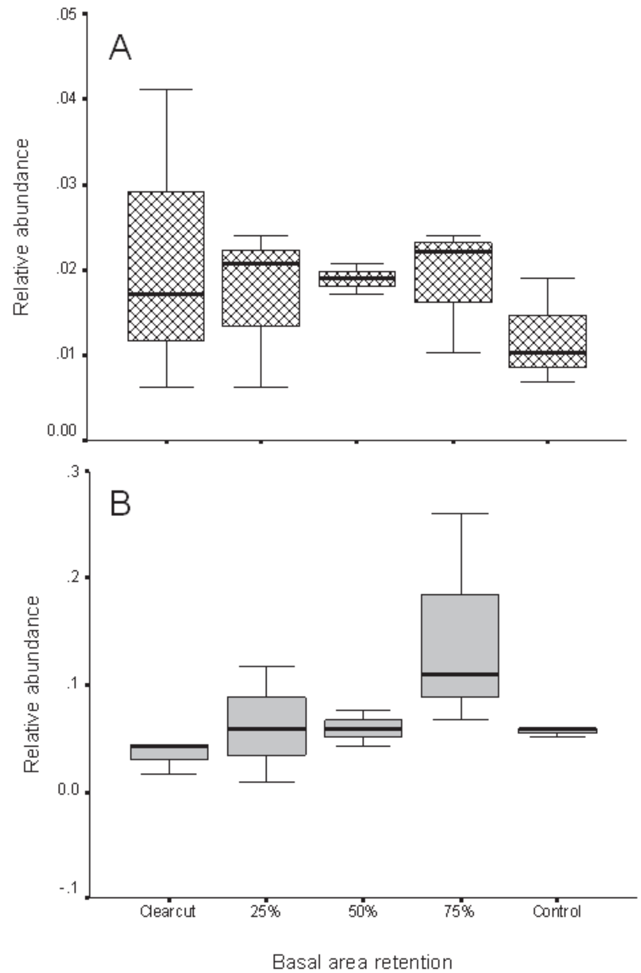

Figure 1—Relative abundance of eastern worm snakes across five tree retention treatments in northern AL, 2002-2005, as measured by drift fences (A) and coverboards (B).

No gravid females were observed on clearcut treatments. The sample percentage comprised of juveniles did not differ among treatments ($\chi^2 = 1.96$, $P > 0.9$) and these percentages ranged from 37 to 51 percent.

Body Size Characteristics

No obvious differences were detected in population structure among the five treatments (fig. 3). Populations on each treatment showed two size classes, one ranging approximately from 60 to 120 mm SVL and another from 140 to 240 mm SVL. Average log-transformed mass: length ratio for male worm snakes was highest in control treatments and lowest in 25 percent retention treatments ($F_{4,10} = 4.36$, $P = 0.031$; fig. 4a), while female log mass to length ratios did not differ among treatments ($F_{4,10} = 0.66$, $P = 0.628$; fig. 4b). A positive relationship (log mass: SVL = 0.024 + 0.428 basal area) was observed between log mass to length ratio of snakes and basal area of the plot of capture for male worm snakes ($R^2 = 0.19$, $P = 0.007$, $n = 37$; fig. 5a). No such relationship was observed for female worm snakes ($R^2 = 0.005$, $P = 0.52$, $n = 54$; fig. 5b).

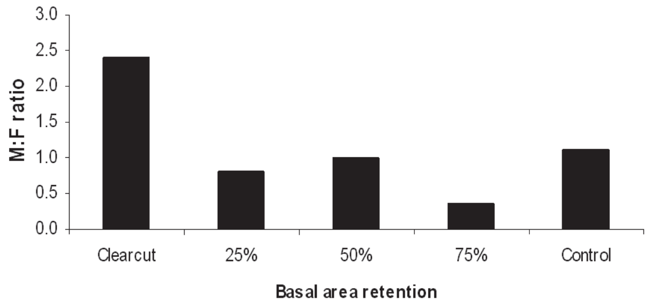

Figure 2—Sex ratios of eastern worm snakes across five tree retention treatments in northern AL, 2002-2005.

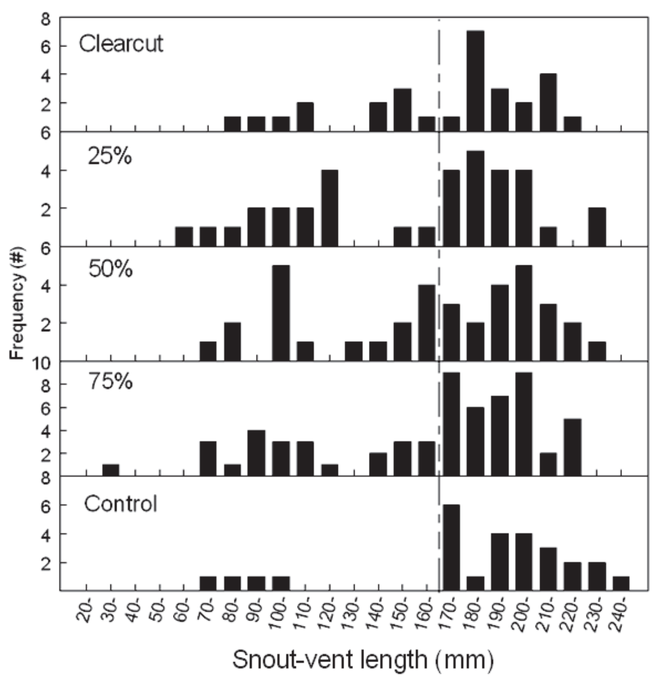

Figure 3—Histogram of size classes (snout-vent length) of eastern worm snakes across five tree retention treatments in northern AL, 2002-2005. Vertical dotted line represents cut-off for juvenile and adult size.

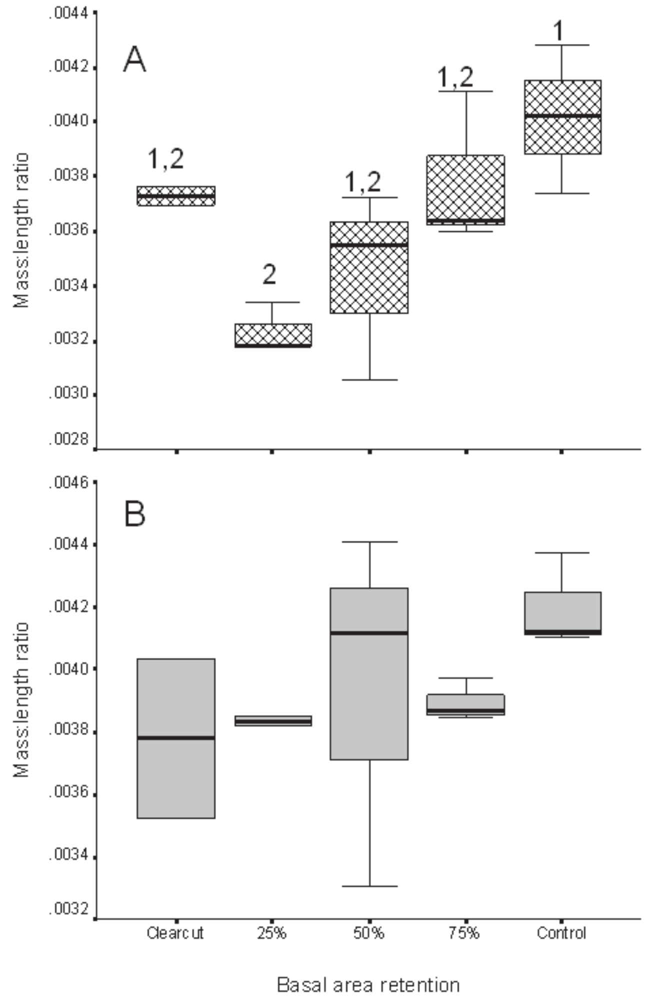

Figure 4—Average log-transformed mass: length ratio for male (A) and female (B) eastern worm snakes across five tree retention treatments in northern AL, 2002-2005.

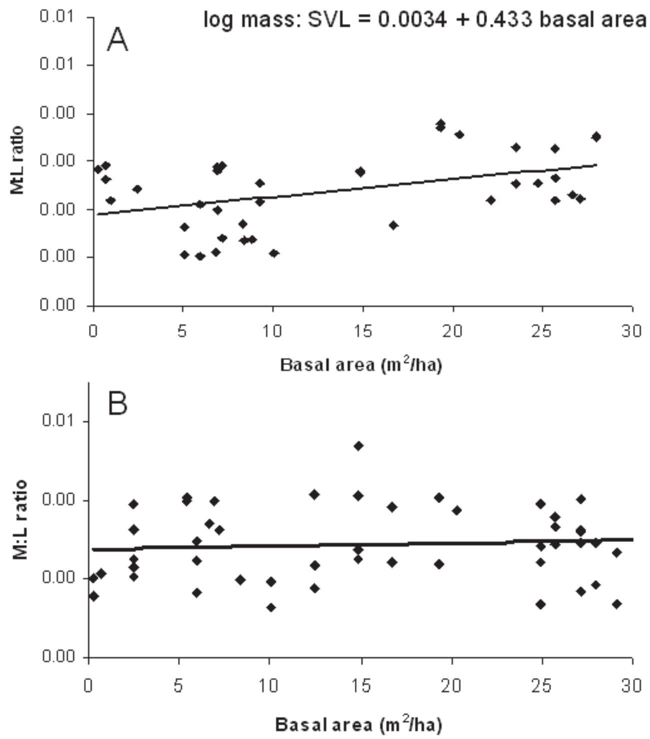

Figure 5—Average log-transformed mass: length ratio for male (A) and female (B) eastern worm snakes vs. average basal area (m^2/ha) at 45 measurement plots, northern AL, 2002-2005.

DISCUSSION

Relative abundance of eastern worm snakes did not differ among retention treatments. This species is often cited as preferring the litter layer in moist forests (Barbour 1960, Ernst and Barbour 1989), but it can also be common in open grassy fields near woodlands (Palmer and Braswell 1995). In KY, eastern worm snakes used recently cut areas and open banks as well as closed canopy areas (Barbour and others 1969). This wide range in habitat use might account for similar abundances of worm snakes across treatments in the present study. Greenberg (2001) found no difference in worm snake abundance between control stands and wind-created canopy gaps in NC.

Sex ratios of small snakes such as worm snakes are usually one male to every female (Clark 1970), but male-biased populations have also been found (Russell and Hanlin 1999). The high ratio of males to female we observed on clearcut treatments could have implications for population dynamics. The lack of gravid females on clearcut treatments suggests low recruitment in these areas. However, the overall high percentage of juveniles in our samples, including clearcut treatments, compared to previous studies (Parker and Plummer 1987) suggests that recruitment is taking place at healthy rates.

Canopy retention treatments were related to body size of male worm snakes. The average mass of a male snake at a given length was larger in control treatments than in 25 percent retention treatments. Also, there was a positive relationship between mass to length ratio and basal area. That is, at a given plot, male worm snakes are more massive at a given length when basal area is higher. This is the first report of such a relationship for a reptile species. This phenomenon is known for salamanders, with some species more massive per length on cut areas (Ash and others 2003, Knapp and others 2003) and other more massive on uncut areas (Karraker and Welsh 2006). It is unknown what, if any, implications these patterns could have for eastern worm snake populations. The differences could be an indication of growth rates or health of individuals. The main prey item of worm snakes is earth worms (Mount 1976), and the observed differences in body size observed in male snakes could be related to differences in worm snake abundance.

Tree harvesting at this geographic location and scale had subtle impacts on the demography of worm snake populations, but did not impact relative abundance of the species. Several aspects of this species uncovered during this study, including the significance of the two size classes present in samples, deserve further research.

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THE INFLUENCE OF RED-BACKED SALAMANDERS (*PLETHODON CINEREUS*) ON NUTRIENT CYCLING IN APPALACHIAN HARDWOOD FORESTS

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Abstract—The use of amphibians as biological indicators of ecosystem health has received considerable attention because of the increasing importance placed upon maintaining biodiversity in forested ecosystems. In this study, we imposed three different eastern red-backed salamander (*Plethodon cinereus*) treatments: 1) low (n = 4; added 0 salamanders to each mesocosm), 2) medium (n = 4; added 3 salamanders each mesocosm) and 3) high (n = 4; added 6 salamanders to each mesocosm), into 3-m^2 *in situ* field enclosures to monitor the potential effects of salamander abundance on the availability of nitrogen (N). Cationic and anionic exchange membranes were placed horizontally under the forest floor and vertically within the A-horizon to index N-availability through time. There was significantly more nitrate ($p < 0.001$) under the forest floor in the low and medium salamander density treatments than the high density treatments. No consistent treatment by time interaction trends were observed for any measures of inorganic N. At this juncture of the experiment, we would reject the research hypothesis that nutrient availability increases as salamander abundance increases.

INTRODUCTION

The role of amphibians in aquatic and terrestrial ecosystems has been the subject of many ecological studies. Of all vertebrate species, amphibians may be the best biological indicators of ecosystem health because of their sensitivity to environmental change (Vitt and others 1990). Although numerous studies have attempted to determine causes of declines of amphibian populations (Alford and Richards 1999), fewer studies have examined the potential implications to ecosystem processes associated with amphibian declines.

The potential top-down trophic effects of amphibian species on leaf litter decomposition, invertebrate communities and nutrient cycling dynamics has been the central theme of many studies (Wyman 1998, Beard and others 2002, Beard and others 2003, Walton 2005, Walton and Steckler 2005, Walton and others 2006). In general, it is considered that small vertebrate predators such as salamanders constitute too little biomass and therefore their impact on nutrient cycling and leaf litter decomposition in terrestrial ecosystems would be minimal at the ecosystem scale (Schlesinger 1997). However, in Appalachian forests, salamanders do constitute a significant portion of the vertebrate biomass (Burton and Likens 1975a, 1975b). In addition, several studies suggest that certain frog and salamander species do regulate certain nutrient cycling processes and impart top-down effects on detrital food webs (Wyman 1998 Beard and others 2002, Beard and others 2003, Walton 2005, Walton and Steckler 2005, Walton and others 2006). Furthermore, biomass alone is not a sufficient indicator of the ecological importance of these vertebrate predators because it ignores waste production and population turnover, which may be important fluxes of nutrients (Beard and others 2002).

The forests of the Appalachian Mountains contain more salamander species than any other temperate region in the world. Salamander species in this region are also the most dominant vertebrate predators (Hairston 1987), suggesting they undoubtedly affect certain trophic food webs. Terrestrial salamanders of the family Plethodontidae are the most abundant forest vertebrate fauna in Appalachia, and red-backed salamanders (*Plethodon cinereus)* are common throughout the eastern United States (Hairston 1949, Burton and Likens 1975a, Burton and Likens 1975b, Hairston 1987). Densities of the eastern red-backed salamander reportedly vary across their range, from 4.0 individuals/m^2 in Virginia (Jaeger 1980), to 0.9/m^2 in Michigan hardwoods (Heatwole 1962), to 0.5/m^2 in hardwood forests of south-central New York (Wyman 1988), and 0.3/m^2 in the Hubbard Brook Experimental Forest of New Hampshire (Burton and Likens 1975b). Due to the extensive geographic range of the red-backed salamander, many *in situ* and laboratory based experiments have used this species to determine and enhance our understanding of the ecological importance of salamanders (Test and Bingham 1948, Hairston 1949, Taub 1961, Heatwole 1962, Burton and Likens 1975a, Burton and Likens 1975b, Jaeger 1980, Hairston 1987, Petranka and others 1993, Wyman 1998, Rooney and others 2000, Welsh and Droege 2000, Davic and Welsh 2004, Morneault and others 2004, Walton 2005, Walton and Steckler 2005, Walton and others 2006). The focus of these studies has ranged from the effects of eastern red-backed salamanders on invertebrate communities, leaf litter decomposition, and nutrient cycling. The sensitivity of plethodontid salamanders to changes in the soil microclimate make them ideal candidates for studying direct and indirect effects on soil processes (Welsh and Droege 2000).

Reported top-down effects of salamanders and other amphibians on decomposition processes and nutrient cycling have varied depending on experimental methodologies, leaf litter substrate, and geographic location. Several studies have hypothesized that salamanders may indirectly affect leaf litter decomposition processes by regulating detritivore prey (Burton and Likens 1975a, Hairston 1987, Davic and Welsh 2004). Wyman (1998) demonstrated with field enclosures containing red-backed salamanders that leaf litter decomposition rates were significantly lower in field enclosures with high densities of salamanders

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compared to enclosures with no salamanders in a forest primarily dominated by American beech (*Fagus grandifolia*). Wyman (1998) attributed the slower decomposition rates to the increased consumption of macrofaunal detritivores responsible for fragmenting leaf litter. In contrast, others have hypothesized that control of invertebrate populations by salamanders would cause decomposition rates to increase because of a reduction in bacterial and fungal consumers, thus releasing microbes (Hairston 1987). Beard (2002, 2003) found that the terrestrial frog, *Eleutherodactylus coqui* (coquì), enhanced nutrient cycling processes and increased leaf litter decomposition rates in a Puerto Rican subtropical wet forest. Beard (2002) concluded that coquìs enhance nutrient cycling processes and accelerate leaf litter decomposition by converting recalcitrant arthropod tissue into more decomposable frog feces and other waste products. Finally, Walton and Steckler (2005) reported no salamander-mediated effects on leaf litter decomposition rates in a laboratory microcosm experiment.

Variation in the top-down effects of amphibians on invertebrate communities, leaf litter decomposition and nutrient cycling warrants additional research that focuses on one or more of the aforementioned ecological processes. Therefore, the primary objective of our research experiment was to determine if variations of eastern red-backed salamander abundance affects nitrogen (N) availability directly under the forest floor and within the A-horizon. Our research hypothesis is that as salamander density increases, N availability will increase.

MATERIALS AND METHODS

Site Description

This study was installed on the Jefferson National Forest approximately 8 km west of Blacksburg, VA in Montgomery County (37°17'38" N, 80°27'27" W). The elevation is approximately 670 m and the average annual precipitation is approximately 101.5 cm. Average annual temperature is 10.8 °C, ranging from 0.3 °C in the winter to 20.7 °C in the summer. The forest cover type is predominately white oak (*Quercus alba* L.) and scarlet oak (*Quercus coccinea* Muenchh.). The study area is in the Ridge and Valley physiographic region, which is comprised of shale, sandstone and limestone sedimentary rocks. Many forest soils in this physiographic region are derived from a combination of sandstone and/or shale in residuum or colluvial parent materials. The soil at the study site is classified as a Clymer soil series (coarse-loamy, siliceous, active, mesic typic Hapludults). The majority of forests in the southern Appalachian Mountains are second growth forests approximately 80 to 100 years in age because of extensive clearcutting and high-grading practices during the late 19th and early 20th centuries.

Experimental Design

Field enclosures (mesocosms) were established randomly using a 5 by 5 grid containing 20 by 20-m cells. Twelve cells were randomly selected for mesocosm locations and treatments were assigned randomly. There were three treatments consisting of red-backed salamanders: 1) low (n = 4; added 0 salamanders to each mesocosm), 2) medium (n = 4; added 3 salamanders each mesocosm) and 3) high (n = 4; added 6 salamanders to each mesocosm). The primary purpose of adding salamanders to the mesocosms was to 'press' the system so that we could examine how above average increases in salamander abundance affect certain ecosystem processes. Each mesocosm was 1.2 by 1.5 m (3 m^2) in size and were 0.25 m tall. Vinyl flashing was buried along the perimeter of each mesocosm to 40 cm. In addition, vinyl flashing was also attached perpendicular to the top of each mesocosm so that approximately 16.5 cm of flashing overhung both within and outside the mesocosms. The purpose of the vinyl flashing was to restrict salamanders from migrating in and out of the mesocosms. Three 30 by 20 by 5 cm rough-cut yellow-poplar (*Liriodendron tulipfera* L.) artificial cover objects (i.e. cover boards) were placed in each mesocosm to monitor salamanders. Cover boards were sampled at least monthly to recapture salamanders.

Following the construction of the mesocosms and placement of the cover boards but before the addition of salamanders, there was a two week acclimation period. During this adjustment period, cover boards were periodically checked and all salamanders found underneath were removed from the mesocosms. We captured 36 adult salamanders outside of the mesocosms and marked them using visible implant fluorescent elastomer (VIE) (Northwest Marine Technology Inc., Shaw Island, Washington, United States). Unique combinations of red, orange and yellow VIE were injected on the ventral side of each salamander. Two injections located posterior to the front legs and two more located anterior to the hind legs were administered. Each color combination was recorded so that we could monitor activity of individual salamanders and identify any salamanders that we did not add (i.e. salamanders with no VIE marks). We removed any captured unmarked salamanders from the mesocosms. All unmarked salamanders captured within the mesocosms were assumed to be within the enclosures at study establishment, but because salamanders remain below the soil surface for extended periods, some were likely unaccounted for during the acclimation period.

Indexing Nutrient Availability

Cation and anion exchange membranes (Ionics Inc., Watertown, MA, United States) were used to index the amount of available ammonium (NH_4^+) and nitrate (NO_3^-) within each mesocosm. Each membrane type (anion and cation) had a surface area of 6.45 cm^2 and was placed directly underneath the forest floor in a horizontal position and within the A-horizon in a vertical position, resulting in a total of 12 membranes for each mesocosm; three anion membranes and three cation membranes for each orientation (horizontal and vertical). Cation and anion membranes were extracted monthly and were replaced with a newly charged set once extracted. To minimize the disturbance to the mesocosms, each enclosure was divided into 189, 25.8-cm^2 cells (i.e. 21 rows consisting of 9 cells per row). Each month, 12 cells were randomly selected for each replacement batch of freshly charged membranes. After a cell was used, it was then disregarded from the randomization procedure and could no longer be selected until all other cells had been used (i.e. each mesocosm contains enough cells for

15 months). All cells that contained a cover board were not used because it could potentially interfere with the monthly salamander sampling since salamanders are sensitive to habitat disturbance. Extracted membranes were placed in individual centrifuge tubes containing 25 ml of 1M KCl. Tubes were shaken for 1 hour and subsequently poured through Whatman #2 filter papers (Whatman International Ltd.). Solutions were analyzed using a Bran and Leubbe TRACCS 2000 Auto-Analyzer (SPX Corporation). Values were converted from parts per million to mg of NO_3^- or NH_4^+ per m^2 of membrane per day (i.e. mg/m/d). In essence, the reported values are an index that represents the average amount of inorganic N available for plant uptake on a daily basis.

Statistical Analysis

One-way repeated measures analysis of variance (SAS 9.0 Institute Inc., Cary, NC) was used to detect potential differences in nutrient availability between the three salamander density treatments through time ($\alpha = 0.05$). There were five extraction periods from July 2006 to December 2006 included in the analysis. Each extraction period was examined individually to analyze the data for treatment by time interactions. When significant differences were detected, we used the Tukey-Kramer differences of least square means test to examine how treatments differed. Three variance-covariance structures (compound symmetry, unstructured and autoregressive) were examined to determine the best model for the data. The compound symmetry variance-covariance model was used for the nutrient data because it had the lowest overall fit statistics, which is the primary determinant for choosing the best model. The selected variance-covariance model was used independently for each response variable: 1) mg-NO_3^-/m^2/d for the vertical and horizontal anion membranes and 2) mg-NH_4^+ /m^2/d for the vertical and horizontal cation membranes.

RESULTS

Effects of Salamander Treatments

The only significant treatment effect across the entire sampling period from July 2006 to December 2006 for available nitrogen was for NO_3^- directly under the forest floor (i.e. horizontally oriented anion membranes; $p < 0.001$; table 1; fig. 1). The low and medium salamander density treatments had significantly more available NO_3^- than the high salamander treatment. Overall nutrient availability values within the horizontally oriented anion membranes also had lower variability than the other membrane orientations. Available NO_3^- within the A-horizon (table 1; fig. 2) and available NH_4^+ under the forest floor (table 1; fig. 3) and within the A-horizon (table 1; fig. 4) were more variable within treatments, resulting in relatively higher p-values.

Effects of Salamander Treatment by Time

Significant treatment by time interactions occurred for each membrane type and orientation across the entire sampling period (table 1). However, because of the disorderly nature of the data (figs. 1-4), treatment by time interactions by each sampling period was examined to discern any potential trends. No significant treatment by time interactions were observed for the July 2006 and August 2006 sampling periods (table 2). Significant time by treatment interactions were observed for available NO_3^- during the September, November and December 2006 sampling periods for the anionic membranes. However, specific treatment differences for the low-, medium-, and high-density treatments varied tremendously for each of the three significant treatment by time interactions (figs. 1 and 2). No specific trends could be discerned except for the steady increase in available NO_3^- from September through December for the low salamander density treatment (figs. 1 and 2). In regards to available NH_4^+ for the cationic membranes, specific treatment by time interactions occurred during September 2006 (fig. 3) for the horizontally orientated cation membranes and during November 2006 (fig. 4) for the vertically oriented cation membranes.

DISCUSSION

Analysis of the effects of salamanders on nutrient cycling of inorganic N, indicates that as salamander abundance increases that there is a decrease in NO_3^- availability directly under the

Table 1—Salamander density treatment results from repeated-measures Analysis of Variance

	p-values	
Response Variable	treatment	treatment x time
Horizontal Anion Membrane	<0.001	<0.001
Vertical Anion Membrane	0.3981	<0.001
Vertical Cation Membrane	0.1283	0.025
Horizontal Cation Membrane	0.7362	0.006

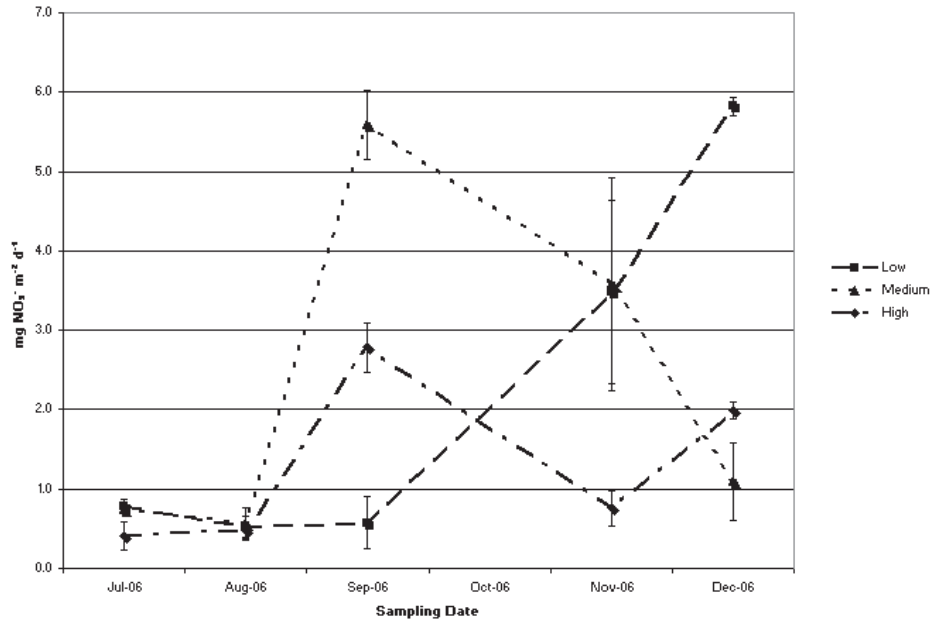

Figure 1—Horizontal anion exchange membrane nutrient index values by sampling date, showing patterns in field enclosures with varying densities of salamanders, Jefferson National Forest, Montgomery County, VA.

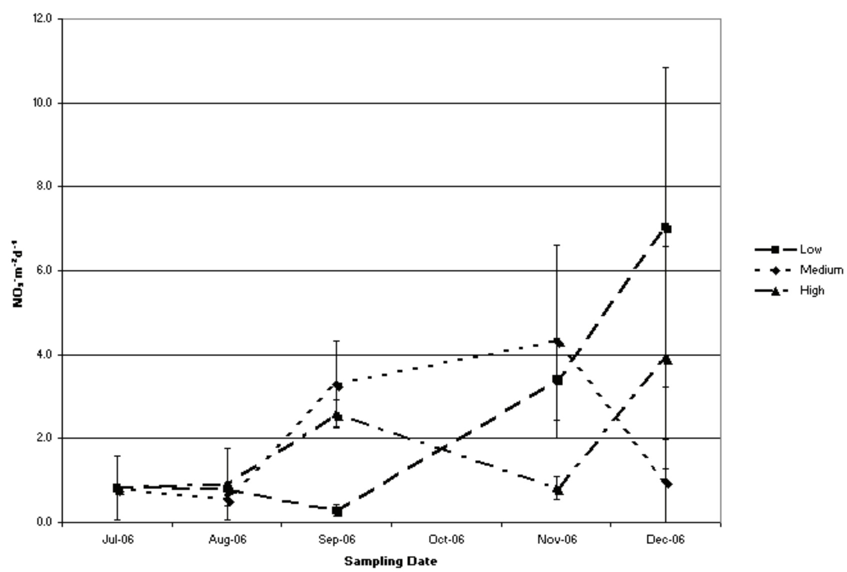

Figure 2—Vertical anion exchange membrane nutrient index values by sampling date, showing patterns in field enclosures with varying densities of salamanders, Jefferson National Forest, Montgomery County, VA.

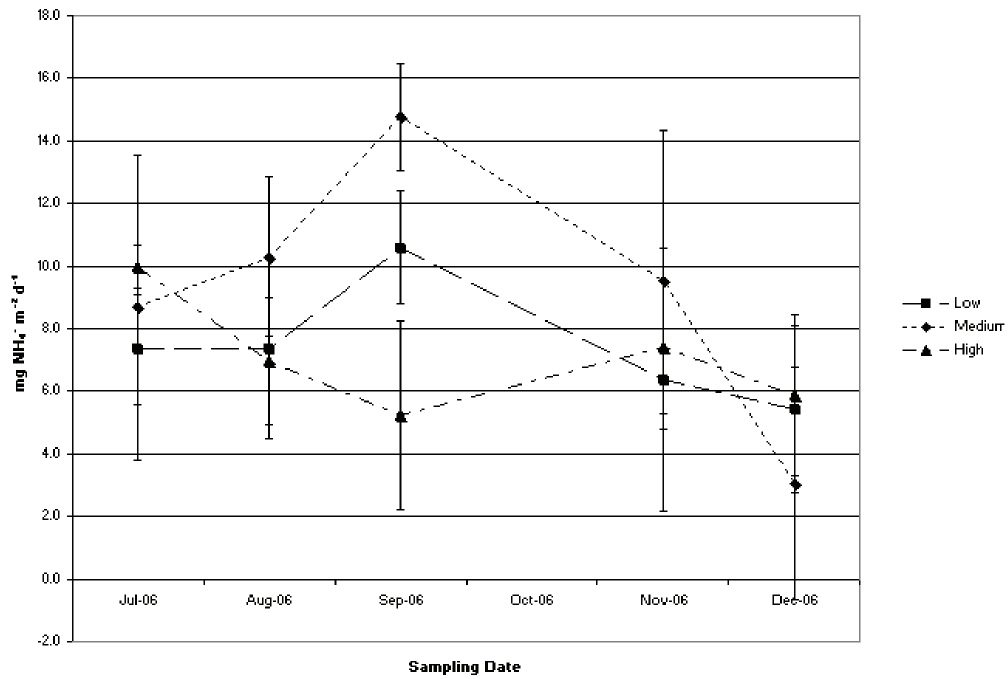

Figure 3—Horizontal cation exchange membrane nutrient index values by sampling date, showing patterns in field enclosures with varying densities of salamanders, Jefferson National Forest, Montgomery County, VA.

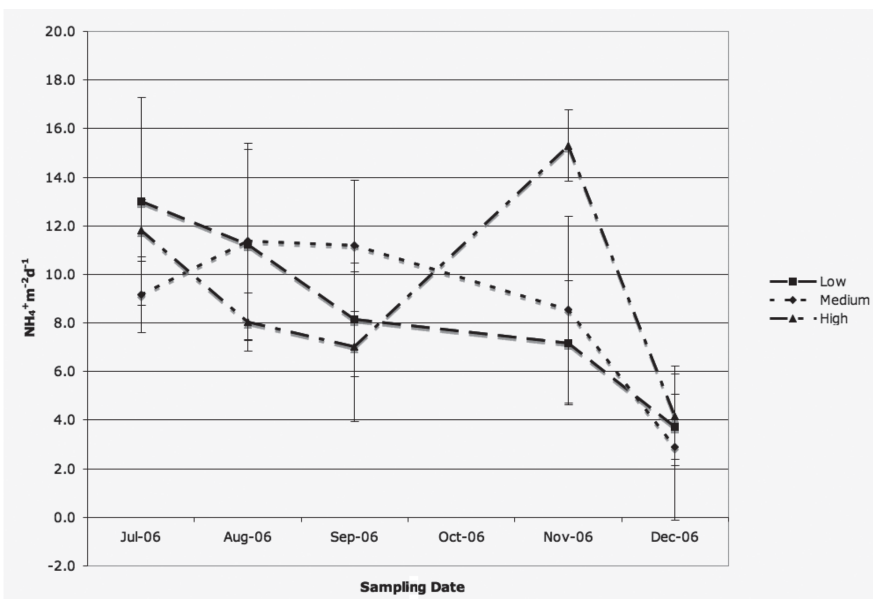

Figure 4—Vertical cation exchange membrane nutrient index values by sampling date, showing patterns in field enclosures with varying densities of salamanders, Jefferson National Forest, Montgomery County, VA.

forest floor (table 1; fig. 1). Forested ecosystems typically adsorb more NH_4^+ than NO_3^- because there are usually higher quantities of NH_4^+ compared to NO_3^-. However, because there is a net cation exchange capacity in Appalachian hardwood forests, NO_3^- is extremely mobile and often leaches through the soil profile. During this process, exchangeable cations such as magnesium, calcium and potassium often bind to the NO_3^- ion as it leaves the system. Therefore, these results potentially suggest that higher salamander abundance could increase base cation retention in these ecosystems.

Some trends have begun to develop as the lower salamander density treatments have steadily increased over the medium and high density treatments from September to December 2006 for available NO_3^- indexed by the anionic membranes (figs. 1 and 2), whereas no specific trends have developed for available NH_4^+ in the forest floor and A-horizon (ts. 3 and 4). However, the early results (5 months) of this relatively long-term experiment (18 months) are not conclusive because of the large amount of variability of NO_3^- and NH_4^+ within the three salamander treatments. In addition, measurements during the spring and summer of 2007 may reveal more consistent treatment effects opposed to the disorderly nature of the data collected and analyzed thus far.

The first two sampling periods (July and August 2006) showed no significant treatment by time interaction for any measure of nutrient availability (table 2). There are two potential reasons for this trend: 1) July and August in the Ridge and Valley Physiographic region in Virginia are exceptionally dry and this area received considerably less than average rainfall during the summer of 2006 or 2) a longer acclimation period may have been required following the addition of the salamander density treatments before measurements began. During the spring months, there is an increase in microbial and insect activity and populations as temperatures rise and as rainfall increases. Spring 2007 nutrient data may indicate higher amounts of available NO_3^- and NH_4^+ as increased salamander pressure could cause significant top-down trophic effects on nutrient availability, invertebrate communities and/or leaf litter decomposition.

At this juncture of the experiment, we reject our research hypothesis that increased salamander densities increase nutrient availability of N. Leaf litter decomposition rates and measures of invertebrate populations and diversity may alter these results once the data are analyzed. There have been conflicting results with some studies involving plethodontid salamanders in regards to the effects these amphibians have on leaf litter decomposition rates, nutrient availability and invertebrate communities. Whether plethodontid salamanders decrease (Wyman 1998) or increase decomposition rates (Hairston 1987) of leaf litter and/or increase the amount of microbial detritivores (Rooney and others 2000) is yet to be fully assessed in this experiment. Concurrent research is examining the effects of red-backed salamanders on invertebrate communities and rates of litter decomposition within these mesocosms.

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Table 2—Salamander density treatment by time interaction results from repeated measures Analysis of Variance

	Treatment x time p-values			
Extraction period	Horizontal anion membrane	Vertical anion membrane	Horizontal cation membrane	Vertical cation membrane
July 2006	0.537	0.999	0.470	0.155
August 2006	0.975	0.931	0.245	0.183
September 2006	<0.001*	0.017*	<0.001*	0.113
November 2006	<0.001*	0.006*	0.323	<0.001*
December 2006	<0.001*	<0.001*	0.370	0.807

* significant differences detected at α <0.05

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AMPHIBIAN AND REPTILE RESPONSE TO PRESCRIBED BURNING AND THINNING IN PINE-HARDWOOD FORESTS: PRE-TREATMENT RESULTS

William B. Sutton, Yong Wang, and Callie J. Schweitzer[1]

Abstract—Analysis of pretreatment data is essential to determine long-term effects of forest management on amphibians and reptiles. We present pre-treatment amphibian and reptile capture data from April 2005 to May 2006 for a long-term study on herpetofaunal response to prescribed burning and tree thinning in the William B. Bankhead National Forest, AL, United States. Experimental design consists of a three by two factorial randomized complete block design. Drift-fence trapping arrays were used to capture 585 animals representing 12 families and 36 species (17 amphibian species and 19 reptile species) during 600 trap nights. No significant treatment difference was found for amphibians and reptiles for Shannon-Wiener indices or species richness. No significant treatment difference was found for amphibian evenness; however, a significant difference was found for reptile evenness ($p < 0.05$) in stands selected for treatment. Study results highlight the importance of collecting pretreatment data to identify pre-existing data trends in stands scheduled for forest management.

INTRODUCTION

Amphibians and reptiles, collectively known as herpetofauna, represent a diverse class of organisms. In the southeast, certain groups of these animals represent the most abundant vertebrates in forest ecosystems. Empirical evidence exists supporting the declines of amphibians (Stuart 2004) and reptiles (Gibbons and others 2000) throughout much of the world. Although increased UV-B radiation and over-collection are harmful to herpetofauna, habitat destruction and alteration represent the greatest risk to amphibians and reptiles (Dodd and Smith 2003). Habitat disturbances exist in many forms; however, not all disturbances are created equally (Pauley 2005). Conversion of forested areas to agricultural and urban areas is likely to have a greater impact upon amphibians and reptiles compared to forest management practices which allow for habitat regrowth. Nevertheless, because forest management practices alter large land areas, it is necessary to evaluate amphibian and reptile response to these disturbances. The degree to which a species will be affected depends largely on life history patterns and type of forest management practice. Amphibian response to forest thinning appears to be negligible (Brooks 1999, Messere and Ducey 1998); however, Grialou and others (2000) found a negative response of some salamanders to forest thinning. Reptiles generally appear to increase following forest thinning (Adams and others 1996) and canopy disturbances (Greenburg 2000). Amphibian response to prescribed burning is dependent on many factors, such as animal life stage, geographic province, and time of year (Pilliod and others 2003), while reptile response appears to be largely species specific (Greenburg and others 1994).

A large body of literature exists regarding the response of amphibians and reptiles to forest management (Russell and others 2004). However, no research exists regarding the effects of forest canopy reduction and prescribed burning on amphibians and reptiles in areas along the Southern Cumberland Plateau. In addition, many studies have taken a retrospective approach without examining the pretreatment herpetofaunal community parameters.

In this paper we examined pretreatment patterns of amphibians and reptiles in pine-hardwood stands scheduled for disturbance. We evaluated the hypothesis that there were no pretreatment differences between treatments for species richness, species evenness, and Shannon-Wiener indices. Data from this study provides support for the need of pretreatment data when analyzing herpetofaunal response to disturbance in forest ecosystems.

METHODS

Study Site

This study took place in the William B. Bankhead National Forest (BNF), located in Lawrence, Winston, and Franklin Counties, of northwestern AL. Bankhead National Forest is a 72 800 ha multi-use forest located in the southern Cumberland Plateau (Gaines and Creed 2003). In the 1930s, loblolly pine (*Pinus taeda*) was planted to re-establish forest conditions in abandoned agricultural and heavily timbered areas, resulting in 31 600 ha of *P. taeda* throughout BNF (Gaines and Creed 2003). Over the past decade, Southern Pine Beetle (*Dendroctonus frontalis*) infestations have affected *P. taeda* stands, producing large numbers of standing dead trees and increased fuel loads, elevating the risk of damaging wildfires. As canopy removal and fire disturbance have been prevented in forests throughout the study area for decades, BNF has initiated a Forest Restoration Plan to reduce wildfire risk and to promote natural forest growth through tree thinning and prescribed fire disturbance. The BNF has not traditionally utilized prescribed fire as a management tool, but has opted to include prescribed burning in the forest restoration plan due to administrative recommendations.

Stand selection criteria required that stands be similar in structure (basal area and stems/ha) and ratio of pine to hardwood tree species. Pretreatment basal area and stems/

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ha ranged as follows: block 1 (24-28 m^2/ha; 539-804 stems/ha), block 2 (20-29 m^2/ha; 552-720 stems/ha), and block 3 (28-34 m^2/ha; 506-920 stems/ha).

Experimental Design

We used a before-after and control-impact (BACI) randomized complete block design. Forest manipulation treatments consist of three thinning levels (no thin, 11 m^2/ha residual basal area), and 17 m^2/ha residual basal area) along with two burn treatments (no burn and burn). The experiment was replicated three times across the landscape. Each plot was approximately 9 ha and was blocked accordingly by time of treatment (year) and location in accordance with the BNF's forest restoration plan. Because we only evaluated pretreatment data in this study, study plot designations were only used to illustrate future treatment conditions.

Herpetofaunal Sampling

Amphibians and reptiles were sampled using drift-fence trapping arrays (Renken and others 2004). A single trapping array composed of three drift fences (61 cm high aluminum flashing) 15 m in length radiating from a triangular box trap was installed in each plot. A central box trap was used because it has proven successful for sampling large bodied snakes (Burgdorf and others 2005). In addition, one large box trap was placed at the terminus of each drift fence (three per array), while two pitfall traps were installed at the midpoint of each drift fence (six per array).

Traps were opened with the block number and order of traps randomly determined *a priori*. Number of trap nights was recorded to determine trapping effort (one trap night is equal to one trap unit being open for a 24 hour period). Traps were checked daily between 0700 and 1200 hours (Central Standard Time) to reduce animal mortality. Upon capture, animals were identified to species, measured (snout-vent length and total length, mm) with a dial caliper (0.1-mm), and weighed with an Ohaus digital scale (0.1 g). Animals were given a trap specific mark to assure that recaptured animals were not counted. Frogs, salamanders, and lizards were toe-clipped, while snakes and turtles were marked via sub-caudal scale-clipping and marginal scute marking, respectively. After marking, animals were released on the opposite side of the drift fence in which capture occurred. We trapped animals between April 2005 and May 2006.

Data Analysis

Species captures were compared using the following bio-diversity measures: species richness, Shannon-Wiener diversity index, and species evenness. Species richness refers to the number of different species found within a community. Shannon-Wiener index is a biodiversity measure that takes into account species richness and species evenness (the relative abundance with which each species is represented in an area). The Shannon-Wiener index was calculated based on

$$H' = -\sum_{i=1}^{s} (p_i)(\ln p_i) \qquad (1)$$

where H' = diversity of species, s = number of species, and p_i = proportion of total sample belonging to the i^{th} species. Shannon-Wiener diversity scores usually fall between 1.5 and 3.5 and are relative to the tested sample (Magurran 1988). Species evenness represents the relative distribution of individuals among species. Evenness is calculated based on

$$E = H' / H\max \qquad (2)$$

where E = evenness measure, H' = Shannon-Wiener function, and H_{max} = maximum value of H' = ln s (number of species). Evenness scores range between 0 and 1, with 1.0 representing a situation in which all species are equally abundant (Magurran 1988).

A general linear model (GLM) was used to compare mean values for species richness, Shannon-Wiener diversity index, and evenness across treatment plots. An alpha level of 0.05 was used for all GLM tests. Tukey tests were used for mean separation. Amphibians and reptiles were analyzed separately due to differences in life history characteristics. Statistical Package for the Social Sciences v. 10.0 (SPSS Inc., USA) was used for all statistical analyses.

RESULTS

A total of 585 unique amphibians and reptiles representing 14 families and 36 species (17 amphibian species and 19 reptile species) were captured during 600 trap nights (Appendix A). The Mississippi slimy salamander (*Plethodon mississippi*) and green frog (*Rana clamitans melanota*) were the most commonly captured amphibians with 206 and 24 individual captures, respectively, while the ground skink (*Scincella lateralis*) and green anole (*Anolis carolinensis*) were the most commonly captured reptiles, with 70 and 33 individual captures, respectively (Appendix A).

Pretreatment Shannon-Wiener indices were not different among the plots, although reptiles had more variability and tended to be highest in 11 m^2/ha plots (mean score = 1.7 ± 0.32), while amphibians were relatively consistent among selected plots (fig. 1). Pretreatment evenness was not different among plots for amphibians, but was different for reptiles ($F = 4.14$; df = 5, 10; $p < 0.03$) (fig. 2); pretreatment reptile evenness was lowest on control plots (mean score = 0.82 ± 0.006) and highest on burn plots (mean score = 0.96 ± 0.003) (fig. 2). Species richness was not different among selected plots, although it tended to have the greatest value on 11 m^2/ha plots for reptiles (mean score = 7.3 ± 1.8) and amphibians (6.7 ± 0.33) (fig. 3).

DISCUSSION

Thirty-six species were captured during the pretreatment survey period. Similar species estimates (43 species) were obtained over a six year period in a Missouri Ozark Forest (Renken and others 2004). The four most common species captured during this study, Mississippi slimy salamander, green frog, ground skink, and green anole, use a variety of habitats and are common throughout the region. Mississippi slimy salamanders are one of the most abundant amphibians that inhabit upland pine-hardwood forests and are able to exploit almost all terrestrial habitats throughout their range, while green frogs inhabit wet areas ranging from ponds to slow moving streams (Mount 1996). Ground skinks are common in upland forest types, while green anoles are common in open and disturbed areas (Mount 1996).

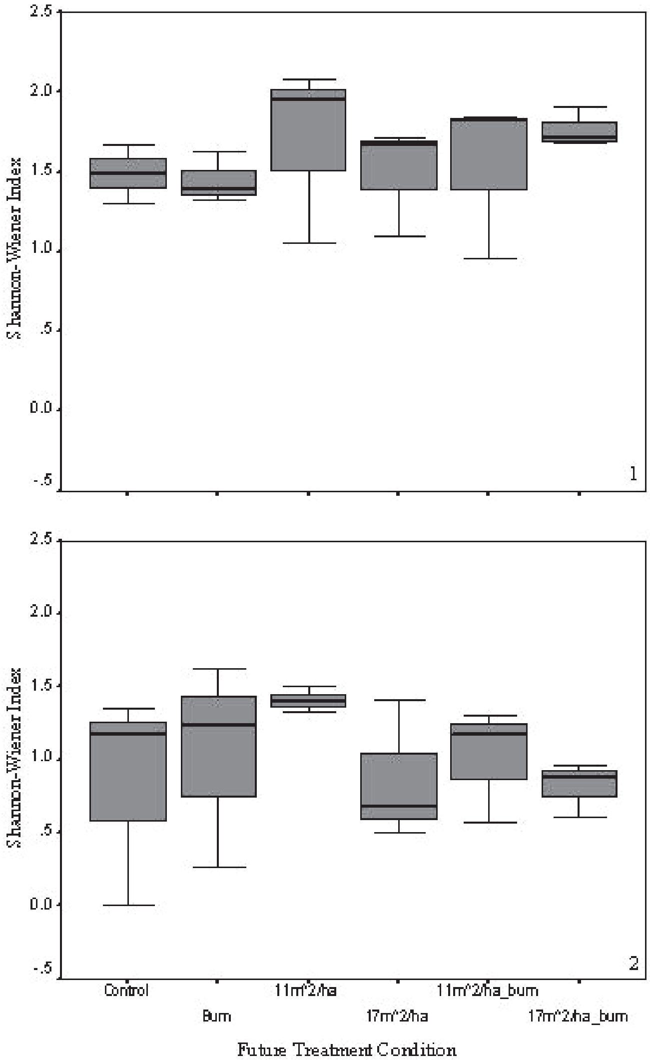

Figure 1—Pre-treatment Shannon-Wiener biodiversity indices for reptiles (1) and amphibians (2) in forest stands of the Bankhead National Forest, AL, U.S.A. No significant differences existed between treatments.

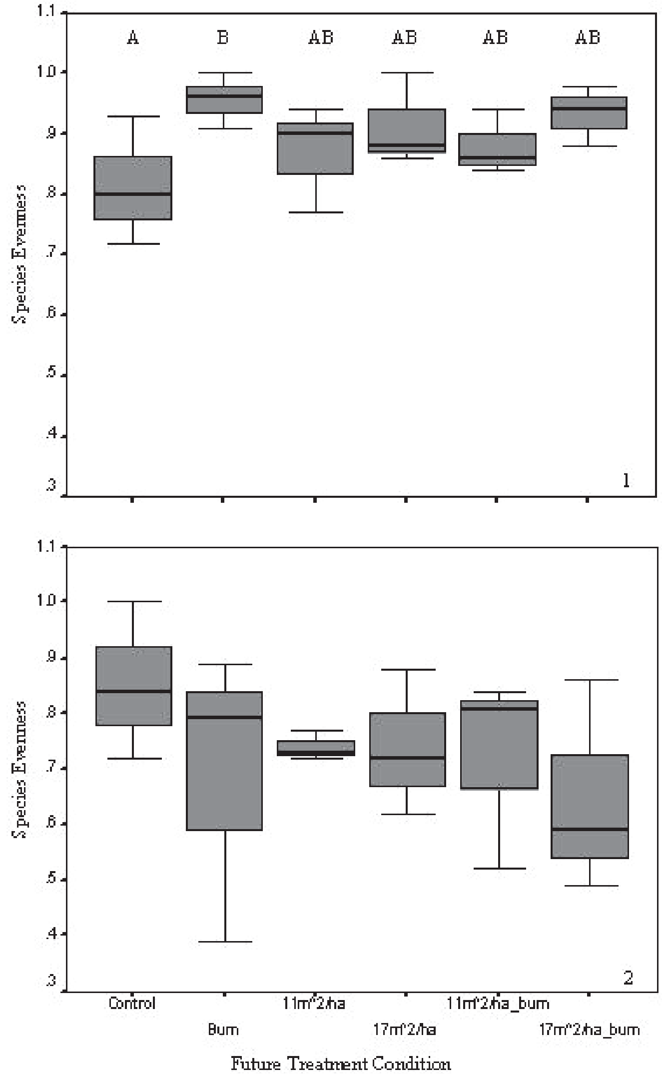

Figure 2—Pre-treatment species evenness biodiversity indices for reptiles (1) and amphibians (2) in forest stands of the Bankhead National Forest, AL, U.S.A. Different letters above boxplots indicate significant differences.

Mean pretreatment biodiversity indices were comparable among plots scheduled for treatments. We found no significant treatment effect for Shannon-Wiener indices, species richness, and evenness for amphibians. This is not surprising, because surveyed stands represent forest stands that were in a “pretreatment” condition and were randomly assigned. Selection criteria required that forest stands in this study had similar disturbance regimes, were between 15 and 45 years of age, were between 210 and 300 m elevation, and were not located along riparian areas. Although all stands examined in this study have been exposed to some type of past forest management disturbance, the study stands had not been exposed to anthropogenic disturbance for at least five years. However, the significant treatment effect found for reptile evenness indicates there is considerable variation between the control and burn plots. Reptile evenness was highest on burn plots indicating that species were represented more evenly than those on control plots. This does not indicate that one plot provides better habitat than another. It indicates that species structure is quite different between these plots. Control stand selection was more constrained than that for other treatment plots. Due to the BNF’s forest restoration plan, there were few stands that could be set aside as untreated (control) stands. Therefore, control stands were located in the Sipsey Wilderness Area, which has not seen anthropogenic disturbances since the wilderness designation in 1975. Therefore, pretreatment species evenness differences may be due the longer time to disturbance in control stands when compared to other stands. This significant difference must be taken into account when comparing the post-treatment data.

Most studies of herpetofaunal response to forest management lack true experimental manipulations, treatment replication, and pretreatment data collection. Russell and others (2004) found only six forest management studies

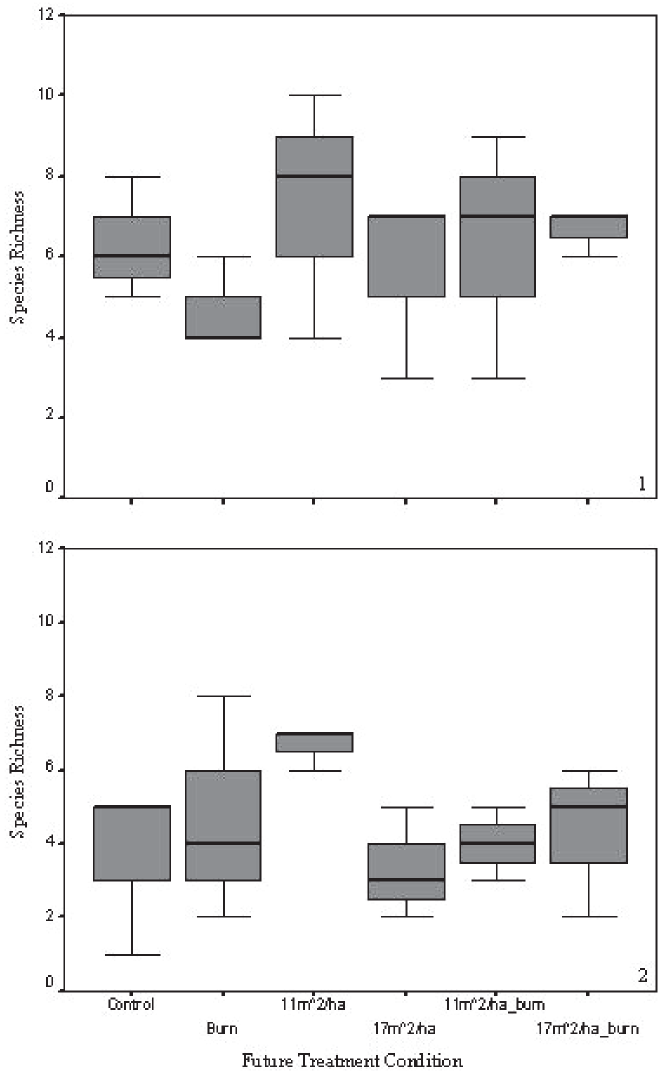

Figure 3—Pre-treatment species richness for reptiles (1) and amphibians (2) in forest stands of the Bankhead National Forest, AL, U.S.A. No significant differences existed between treatments.

that met these criteria. Attempts should be made to include these criteria into future forest management studies; this will increase strength of conclusions from these studies (Sallabanks and others 2000). Our findings indicate the importance of pretreatment data for large-scale forest management studies. We recommend that researchers who wish to implement similar studies should work closely with land managers during project planning periods to assure that pretreatment data can be collected.

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We thank the Bankhead National Forest for assistance with study implementation. We also thank the EPA-STAR program for providing WBS with a fellowship. The research at Bankhead National Forest was supported by the National Science Foundation and Alabama A&M University. Funding and logistic support from the USFS Southern Research Station was greatly appreciated. We thank Zach Felix and Jill Wick for previous reviews of this manuscript.

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Appendix A—Pre-treatment amphibian and reptile species captures in Bankhead National Forest, Alabama, U.S.A.

Species List	Number Captured
Order Anura	
Family Bufonidae	
Fowler's toad (*Bufo fowleri*)	14
Family Hylidae	
barking treefrog (*Hyla gratiosa*)	1
grey treefrog (*Hyla chrysoscelis*)	1
mountain chorus frog (*Pseudacris brachyphona*)	3
Family Microhylidae	
eastern narrowmouth toad (*Gastrophryne carolinensis*)	9
Family Pelobatidae	
eastern spadefoot (*Scaphiopus holbrookii*)	
Family Ranidae	
American bullfrog (*Rana catesbeiana*)	14
green frog (*Rana clamitans melanota*)	24
pickerel frog (*Rana palustris*)	7
southern leopard frog (*Rana sphenocephala*)	9
Order Caudata	
Family Ambystomatidae	
marbled salamander (*Ambystoma opacum*)	3
spotted salamander (*Ambystoma maculatum*)	4
Family Plethodontidae	
northern red salamander (*Pseudotriton r. ruber*)	14
northern zigzag salamander (*Plethodon dorsalis*)	19
Mississippi slimy salamander (*Plethodon mississippi*)	206
southern two-lined salamander (*Eurycea cirrigera*)	2
Family Salamandridae	
red-spotted newt (*Notophthalmus v. viridescens*)	1
Order Squamata	
Suborder Lacertilia	
Family Phrynosomatidae	
fence lizard (*Sceloporus undulatus*)	12
Family Polychridae	
green anole (*Anolis carolinensis*)	33
Family Scincidae	
broad-headed skink (*Eumeces laticeps*)	17
five-lined skink (*Eumeces fasciatus*)	21
ground skink (*Scincella lateralis*)	70
Suborder Serpentes	
Family Colubridae	
black king snake (*Lampropeltis getula nigra*)	5
black racer (*Coluber c. constrictor*)	9
eastern corn snake (*Elaphe guttata*)	4
eastern garter snake (*Thamnophis s. sirtalis*)	10
eastern worm snake (*Carphophis a. amoenus*)	4
midland brown snake (*Storeria dekayi wrightorium*)	1
midland rat snake (*Elaphe spiloides*)	6
midland water snake (*Nerodia sipedon pleuralis*)	1
red-bellied snake (*Storeria o. occipitomaculata*)	1
red milk snake (*Lampropeltis triangulum syspila*)	1
southern ringneck snake (*Diapdophis p. punctatus*)	4
Family Viperidae	
southern copperhead (*Agkistrodon c. contortrix*)	32
timber rattlesnake (*Crotalus horridus*)	4
Order Testudines	
Family Emydidae	
eastern box turtle (*Terrapene c. carolina*)	3

HABITAT USE OF TWO SONGBIRD SPECIES IN PINE-HARDWOOD FORESTS TREATED WITH PRESCRIBED BURNING AND THINNING: FIRST YEAR RESULTS

Jill M. Wick and Yong Wang[1]

Abstract—We evaluated habitat use and home range size of hooded warblers (*Wilsonia citrina*) and worm-eating warblers (*Helmitheros vermivorus*) in six treated mixed oak-pine stands on the Bankhead National Forest in north-central AL. Study design is a randomized complete block with a factorial arrangement of three thinning levels (no thin, 11 m^2/ha residual basal area, and 17 m^2/ha residual basal area) and two burn treatments (burn and no burn). Data used in this analysis included those collected from the first of three replications during the first post-treatment year, between May and July 2006. Habitat use and territory size were quantified via territory mapping based on radio telemetry and burst sampling methods. Habitat variables collected within and outside territories were used to determine habitat preferences. Our results suggest that birds on the treatment plots relied on areas left untreated in the stand or uncut areas adjacent to cut stands. Home ranges of both species were relatively large. Habitat within home range had a greater slope, canopy cover, number of trees, basal area, and tree species richness than unused areas.

INTRODUCTION

Many migratory bird species have experienced population declines in past decades, primarily due to loss of suitable habitat from anthropogenic disturbances (Askins and others 1990, Robbins and others 1989). One of the factors contributing to habitat loss for many bird species in the United States is forest management practices that prevent natural disturbance (i.e., fire suppression, pine plantations) (Rappole and McDonald 1994), leading to the breakdown of ecological processes and “unhealthy” forest ecosystems.

To restore forest ecosystem health, canopy reduction and prescribed burning have been used to simulate natural disturbance. Early research shows that such disturbances can affect resource abundance and availability on which birds rely (Wiens 1989). Disturbance can trigger changes in habitat, food and nest-site availability, predation, and nest-parasitism (Wiens 1989). Such alterations can affect the likelihood of breeding success.

Territory size varies depending on habitat quality, with poor quality habitat resulting in the need for a larger territory (Mazarolle and Hobson 2004). During the breeding season, the purpose of defending a territory is to ensure sufficient resources to raise offspring (Wilson 1979). Territory size is a function of expected prey abundance which birds base on structural habitat cues (Smith and Shugart 1987). There appears to be a habitat quality gradient defined by relationships between habitat structure and prey abundance which influence variation in territory size (Smith and Shugart 1987).

Because birds rely on available resources in their territory, different silvicultural treatments may result in birds having differing territory sizes to adequately access resources and successfully fledge young. Research has focused on the effect of fragmentation on territory size and resource abundance (Mazerolle and Hobson 2004, Norris and others 2000, Roberts and Norment 1999), but few experimental studies have been implemented to determine the effect of silvicultural treatments on avian ecology.

In this study, we evaluated of the effect of forest disturbances, specifically thinning and prescribed burning, on the avian community. We examined disturbance effects on avian home range size and one of the mechanisms (habitat structure and composition) responsible for changes in avian population demographics. The objectives of this study are to (1) determine home range and core area size of two songbird species in areas treated by thinning and burning, (2) determine the extent to which songbirds are using treated areas, and (3) compare differences in habitat within and outside of songbird home ranges. Results presented here are based on data collected during the first post-treatment year (2006).

METHODS

Study Sites

This study took place in the northern third of the William B. Bankhead National Forest (BNF) located in Lawrence and Winston counties, northwestern AL. Much of this area has been infested by the southern pine beetle (*Dendroctonus frontalis*). Therefore, to restore forest health, BNF has initiated a Forest Health and Restoration Project (Gaines and Creed 2003), which provided the experimental framework for this project. Eighteen study plots were located on upland sites composed of 20 to 35 year old loblolly pine (*Pinus taeda*). Average plot size was 9 ha and plots had similar location, age, and stand density.

Experimental Design

Research followed a randomized complete block design. Forest manipulations consisted of two factors, thinning (no thin, 11 m^2/ha residual basal area, and 17 m^2/ha residual basal area) and burning (no burn and burn). Each of these were replicated three times and blocked by year. The results

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in this paper are from the first block of treatments (six study plots). Treatments were completed between August 2005 and February 2006. During thinning, hardwoods were preferentially retained. All thinning was completed before fire prescriptions. Prescribed burning was performed in the dormant season (January to March) with low-burning surface fires.

Target Species

The hooded warbler (*Wilsonia citrina*) and the worm-eating warbler (*Helmitheros vermivorus*) were chosen as target species because of their pretreatment abundance and their life history traits. Both are insectivorous forest-interior species that inhabit mixed hardwood forests (Evans Ogden and Stutchbury 1994, Hanners and Patton 1998). Hooded warblers prefer small openings and a shrub understory for nesting (Evans Ogden and Stutchbury 1994), whereas worm-eating warblers prefer areas with high canopy cover and patches of shrub cover and nest on the ground, usually on slopes (Hanners and Patton 1998).

Home Range Estimation

Males of each target species were captured using song playback to attract them into mistnets. Each captured bird was banded with a US Fish and Wildlife Service numbered aluminum band and plastic color bands to aid in individual identification. A radio transmitter (Model BD-2, 0.065 g [4-5 percent of body mass], Holohil Systems, ltd.) was also attached to the back of the bird using a figure-8 harness (Rappole and Tipton 1991) made of cotton thread and secured with super glue. All birds were released immediately after processing and tracked after 48 hours to allow them to adjust to the leg bands and radio transmitter.

Birds were tracked using burst sampling (Barg and others 2005). Bird locations were recorded at 60 second intervals for a total of 30 points per session. If the bird was lost during the session, recording temporarily stopped until the bird could be relocated; each session lasted between 30 and 80 minutes. Each bird was tracked every three to four days, and we performed as many sessions as possible before the transmitter battery died. Each location was recorded using a handheld global positioning system (eTrex Vista, Garmin Ltd.) and downloaded into ArcGIS v. 9.1 (ESRI) for analysis.

Habitat Analysis

Six habitat plots were established for each bird after the breeding season – three inside the home range and three outside the home range but within the treated area. Habitat features were measured after the breeding season (July) using concentric circular plots with a method modified from James and Shugart (1970). We recorded species and size class of all trees greater than 7.62 cm diameter at breast height (d.b.h.) and basal area within a 11.3-m radius (0.04 ha); the number of woody and herbaceous stems within a 5-m radius; and the percent ground cover within a 1-m radius. Percent canopy cover, vertical cover, and litter depth were recorded in cardinal directions 5 m from the plot center. Aspect and percent slope was recoded at each plot center.

Statistical Analysis

A t-test was used to determine differences between habitat within and outside of home ranges after calculating averages for each bird based on three plots. Statistical tests were carried out at the 0.05 significance level using SPSS v.10.0. Home range and core areas were delineated with the Home Range Tools extension for ArcGIS v. 9.1 (Rogers and others 2005). Home ranges were estimated using adaptive kernel density estimators with a smoothing parameter selected through least squares cross validation (Seaman and Powell 1996). The resulting home range kernel was divided into probability contours in increments of 10 percent, and the center 10 percent was considered as the core area.

RESULTS

Captures

Twenty-three birds were caught and banded (13 worm-eating warblers and 10 hooded warblers). Fifteen of these birds were consistently seen on the plots throughout the season, two birds disappeared mid-season, and eight birds were never seen again after banding. Of the 15 'regulars', we tracked six birds (two worm-eating warblers and four hooded warblers). We attached radio transmitters to all but one of these birds. The majority of the tracked birds were located in the thinned plots (table 1). An average of 184 points per bird was collected.

Home Range and Habitat Use

Average home range size was 14.58 ha (range: 0.50 to 31.01 ha) for hooded warblers and 20.45 ha (range: 20.14 to 20.75 ha) for worm-eating warblers. The average core area was 0.38 ha for hooded warblers and 0.64 ha for worm-eating warblers. Average home range located within the treated area was 45.2 percent (range: 26.2 to 71.5 percent) for hooded warblers and 40.2 percent (range: 30.33 to 50.1 percent) for

Table 1—Distribution of target species across treatment plots

Treatment	Caught/Banded ('Regulars')	Tracked
Control	4 (3 WEWA[a], 1 HOWA[b])	0
Thin	9 (4 WEWA[a], 5 HOWA[b])	5 (1 WEWA[a], 4 HOWA[b])
Burn	0	0
Thin and Burn	2 (1 WEWA[a], 1 HOWA[b])	1 (WEWA[a])

[a] Worm-eating warbler *(Helmitheros vermivorus*)
[b] Hooded warbler (*Wilsonia citrina*)

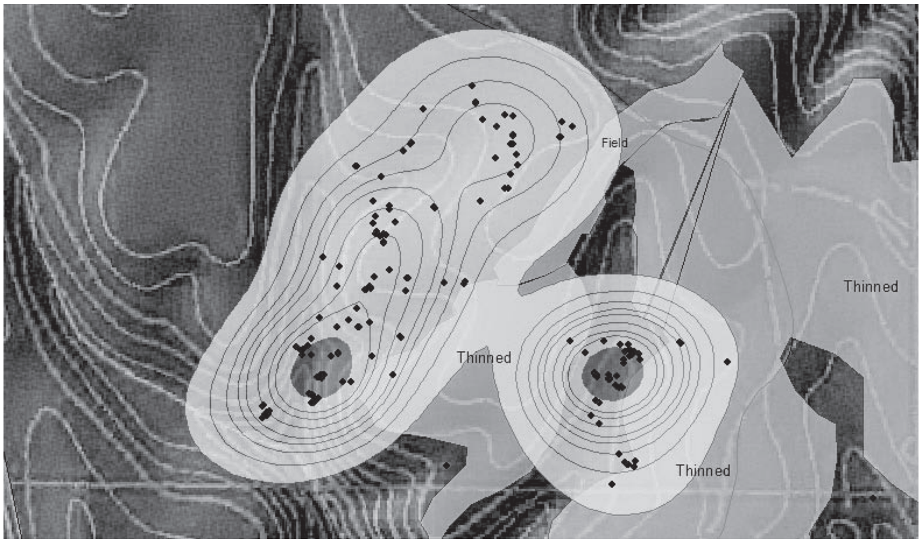

Figure 1—Map of a hooded warbler home range, Bankhead National Forest, May – June 2006. Light grey indicates the bird's home range (center darker area is the core area) and dark grey indicates the thinned area, the remaining area was not treated. Closed circles are locations of individual bird observations.

worm-eating warblers (fig. 1). Habitat within home range was higher in slope, canopy cover, the number of trees, basal area, and tree species richness than unused areas (table 2).

DISCUSSION

Wilson (1979) defines home range as the total area which an animal inhabits. For songbirds, it often is larger than the bird's territory and encompasses the total area the bird travels. The entire home range is not necessarily defended as the territory is; however, the defended territory is included within the boundaries of the home range. The core area is the area of heaviest regular use within the home range, and it may be parallel to the defended territory. For songbirds, the territory is the easiest area to measure because the individual defends this area by singing; therefore, it can be determined by identifying the locations where the bird sings. The home range proves harder to identify because the bird does not always "advertise" his location by singing. Radio telemetry makes it possible to locate the birds in all parts of its home range, even when not singing.

Previously reported territory size ranges from 0.50 ha to 6.54 ha for hooded warblers (Evans Ogden and Stutchbury 1994, Norris and others 2000) and is approximately 1.72 ha for worm-eating warblers (Hanners and Patton 1998). There no information is available regarding home range size for either species. The home range sizes found in this study (15 ha for hooded warbler and 20 ha for worm-eating warbler) were relatively large. This could indicate the habitat quality of our study site was low. A larger area is needed to accommodate the bird's needs at poorer sites. It is evident in the distribution maps that the birds probably used the thinned areas as a way to access non-thinned areas that were separated by thinned areas. For some individuals, there were no observation points collected within the thinned areas; however the home range often extended across the thinned plot where the bird moved to access untreated areas (fig. 1).

Birds are choosing habitat that has more trees, greater canopy closure, and higher tree variety than habitat available in thinned areas. This could be because more vegetation provides them with more cover and nest sites. The habitat

Table 2—Significant habitat variables within (used) and outside (available) of bird home ranges

Habitat Variable	Used	Available	p-value
Slope	22.24 %	8.53%	0.0001
Canopy cover	80.82 %	65.18%	0.0003
Number of trees[a]	24.67	14.8	0.0022
Tree species richness	6.93	4.97	0.0053
Basal area	70.25 ft^2 per ac	54.7 ft^2 per ac	0.05

[a] Number of trees in 0.01 acre circular plot.

the birds are choosing most likely has greater food resources than the thinned areas. Increased vegetation is positively correlated with food availability (Marshall and Cooper 2004, White 1984) and many arthropods are positively associated with interior forest, away from edges (Kilgo 2005). Little information is available on the specific habitat requirements of either species, but both species inhabit the forest interior and are not as productive in fragmented forests as in contiguous forests (Gale and others 1997, Kilgo 2005, Norris and others 2000).

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SNAG RECRUITMENT AND MORTALITY IN A BOTTOMLAND HARDWOOD FOREST FOLLOWING PARTIAL HARVESTING: SECOND-YEAR RESULTS

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Abstract—Snags are defined simply as standing dead trees. They function as an important component of wildlife habitat. Unfortunately, little information has been gathered regarding snags in bottomland forest ecosystems. We initiated a study to determine the effects of harvesting on the flora and fauna of a bottomland hardwood ecosystem adjacent the Mississippi River in Issaquena County, MS. Treatments included complete harvesting (clearcut), partial harvesting, and an unharvested control. Our objective was to determine the density, recruitment, and "mortality" of snags. We recorded 189 snags ≥ 10-cm diameter at breast height (d.b.h.) during pretreatment measurements. Sugarberry (*Celtis laevigata* Willd.) and boxelder (*Acer negundo* L.) comprised 35 and 27 percent of snags, respectively. Two years following harvest, no differences were found in snag density, cumulative mortality, or recruitment between the partial harvesting and controls. However, differences were found between these two treatments and the complete harvest. Long-term data are needed before definitive statements can be made regarding management impacts on snags in bottomland hardwood ecosystems.

INTRODUCTION

The Society of American Foresters defines tree snags as standing, generally unmerchantable, dead trees from which the leaves and most of the branches have fallen (Helms 1998). For purposes of our study, we view tree snags differently, because merchantability has little to do with ecological function. Further, the above definition does not take into account trees that have recently died and retain many of their branches, including small twigs. Therefore, we define tree snags simply as standing dead trees (Cornell University N.d.).

Snags provide several key ecosystem functions. They are used by many wildlife species including birds and small mammals (Cain 1996, Connor and others 1994, Dingledine and Haufler 1983, Hamel and others 1982, Hamilton 1943, Ohmann and others 1994, Runde and Capen 1987, Sinclair and others 1977, Styskel 1983). These species use snags for nesting, foraging, perching, and roosting (Harlow and Guynn 1983, Land and others 1989, Rosenburg and others 1988, Sabin 1991); thus, including snags in forest management plans is critical to many species (Stone and others 2002, Wilson and others 2007). Snags also serve as refugia for other species including insects and fungi (Franklin and others 1981, Harmon and others 1986). In a sense, snags can be just as "alive" as living trees, serving as their own dynamic ecosystem.

Research into snag recruitment and "mortality" is limited. Previous research has focused primarily on western conifer species, including ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) and Douglas-fir (*Psuedotsuga menziesii* (Mirb.) Franco) due to their long persistence time (Franklin and others 1981, Harris 1999). Snag classification systems that define specific decay stages have been well established for these species (Franklin and others 1981). Less is known about hardwood snags (Fan and others 2003, Yamasaki and Leak 2006), especially in southern bottomland ecosystems (Conner and others 1994). Greater rainfall and more humid conditions in the southeastern United States lead to greater decomposition rates and higher biological productivity resulting in potentially greater turnover rates for hardwood snags. Our objective was to document snag density, recruitment and mortality in the Mississippi River batture land as part of a larger study investigating changes in floral and faunal communities following complete and partial harvesting in a bottomland hardwood ecosystem (Lockhart and others 1996). Our hypotheses were (1) greater snag recruitment would occur in the partial harvest treatment in the short-term due to harvesting activities and (2) greater snag recruitment would occur in the long-term in the unharvested controls due to a greater number of available candidate trees compared to the harvested treatments.

MATERIALS AND METHODS

The study site is located on Pittman Island in Issaquena County, MS (32° 55' N, 91° 09' W) within the unprotected lands (batture) along the Mississippi River. The site is characterized by ridge and swale topography due to channel migration of the Mississippi River (Mitsch and Gosselink 1993). Soils vary but are composed primarily of Commerce silt loam (fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts), Sharkey clay (very fine, smectitic, thermic Chromic Epiaquerts), Bowdre silty clay (clayey over loamy, smectitic, thermic Fluvaquentic Hapludolls), and Robinsonville very fine sandy loam (coarse-loamy, mixed, superactive, nonacid, thermic Typic Udifluvents). Climate is characterized as humid and warm. Average high temperature is 28° C in July, and average low temperature is 6° C in January. Precipitation averages 142 cm per year with the greatest monthly average in March (15.7 cm) and the lowest monthly average in August (6.8 cm) (Information source: Rolling Fork, MS, weather station located about 25 km northeast of Pittman Island, http://www.

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msstate.edu/dept/GeoSciences/). Periodic summer droughts occur in the region. Past management activities in the forest included a partial harvest in 1979 and 1980 and infrequent light harvests before 1969. Species composition by number of trees per ha ≥ 10 cm diameter at breast height (d.b.h.) included sugarberry (*Celtis laevigata* Willd.; 62 percent), sweet pecan (*Carya illinoensis* (Wang) K. Koch; 8 percent), boxelder (*Acer negundo* L.; 8 percent), American elm (*Ulmus americana* L.; 8 percent), green ash (*Fraxinus pennsylvanica* Marsh.; 3 percent) and Nuttall oak (*Quercus nuttallii* Palmer; 2 percent).

Two harvesting (reproduction method) treatments, clearcut and selection, were implemented during the winter of 1995/1996. Each treatment and an unharvested control were located on 20-ha treatment plots and replicated three times for a 180-ha study area. In the clearcut treatment (hereafter referred to as complete harvest), all commercial stems were removed during the logging operation. A followup treatment consisted of felling all remaining stems ≥ 5 cm d.b.h. In the selection harvest (hereafter referred to a partial harvest), tree marking was done according to Anderson-Tully Company guidelines (see Lockhart and others 2005 for more information). Within the partial harvest treatment, a combination of single-tree and group selection harvests was used to remove 1/3 to 1/2 the basal area. Tree species favored for management included green ash, Nuttall oak, sweet pecan, and sugarberry.

Prior to harvest (1995), sixteen 0.1-ha circular plots were systematically established in each treatment plot (144 plots total). All snags ≥ 10-m d.b.h. were recorded by species. Distance and azimuth from plot center were also recorded. In addition to pretreatment measurements, first and second year post-harvest measurements were conducted to determine changes in pretreatment snag condition and to document recruitment of new snags. Data were analyzed using analysis of variance (SAS, Inc. 1985). Duncan's multiple range test was used to separate treatment means if significant differences (alpha ≤ 0.05) were found in the analysis of variance.

RESULTS AND DISCUSSION

A total of 189 snags (mean = 13.1 snags/ha) were tallied across the study site prior to treatment application. These snags represented 14 species; sugarberry and boxelder comprised the majority at 35 and 27 percent, respectively (fig. 1). Eight percent of the snags were of unknown species due to advanced decay. The snags were evenly distributed among the designated treatments with a range of 14.0 snags/ha in the controls to 12.1 snags/ha in the complete harvest (fig. 2–1995 bars).

Following the 1996 growing season, 66 percent of the original 189 snags either perished or broken off below d.b.h. These 125 snags represented first year, post-treatment snag "mortality." A significant difference occurred in snag mortality between the complete harvest and the unharvested control (p = 0.02; fig. 3). Greater snag morality was expected within the complete harvest, because all remaining stems ≥ 5 cm d.b.h. were felled in a follow-up operation. Unfortunately, two snags were not felled during this treatment resulting in only

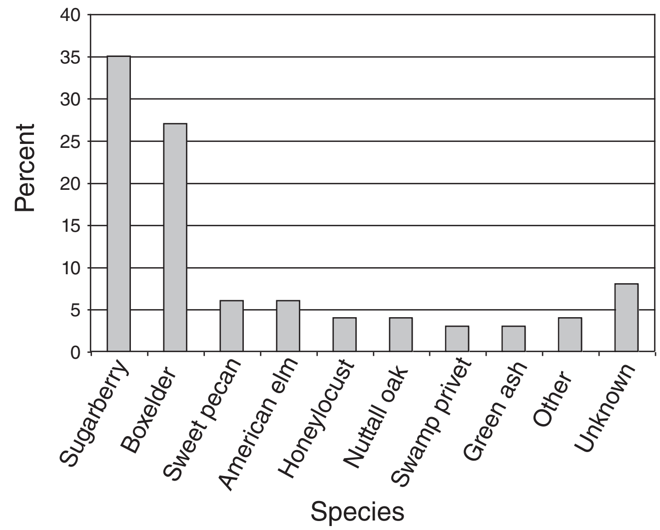

Figure 1—Pre-treatment snag percentage by species on the Pittman Island study site, Issaquena County, MS.

97 percent snag mortality. No significant difference was found between the complete and partial harvest and between the partial harvest and unharvested control due to the high variability associated with the partial harvest (fig. 3). Two-thirds of the pretreatment snags in the partial harvest were lost one year following harvesting while 1/3 of the snags were lost in the unharvested control during the same time; therefore, it is plausible that about 1/2 of the snags lost in the partial harvest can be attributed to the harvesting operation or its aftereffects (fig. 3).

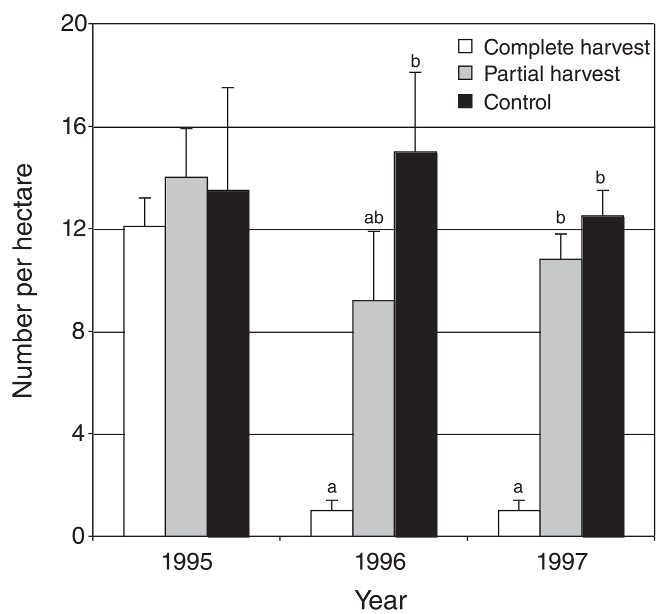

Figure 2—Number of snags per hectare by year and treatment on the Pittman Island study site, Issaquena County, MS. Bars with different letters within a year are significantly different at p ≤ 0.05.

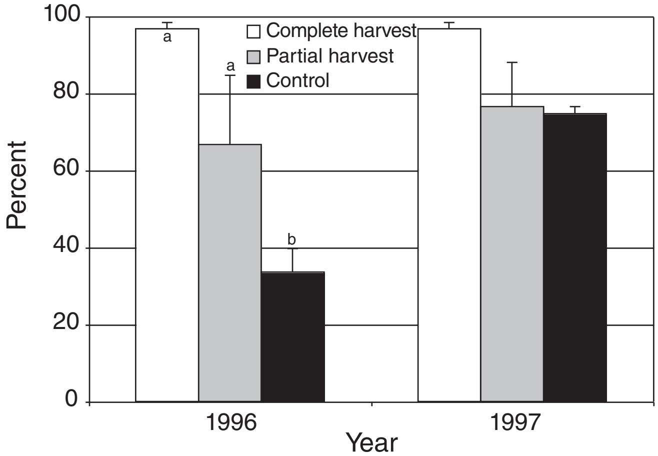

Figure 3—Cumulative mortality of pre-treatment snags by year and treatment on the Pittman Island study site, Issaquena County, MS. Bars with different letters within a year are significantly different at $p \leq 0.05$.

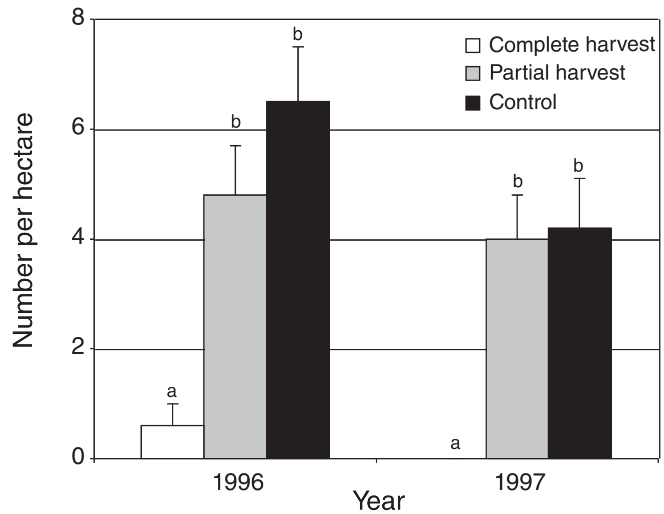

Figure 4—Number of snags recruited per hectare by year and treatment on the Pittman Island study site, Issaquena County, MS. Bars with different letters within a year are significantly different at $p \leq 0.05$.

Recruitment of new snags during the 1996 growing season ranged from 0.6 to 6.5/ha for the complete harvest and unharvested control, respectively (fig. 4). Three snags were recruited in the complete harvest. Two snags were boxelder stems that were 20 and 24 cm d.b.h. The third snag was a 62 cm sugarberry that was only about two meters tall, because the main stem broke off during harvest operations. These stems were also missed during the follow-up treatment. Greater recruitment of snags occurred in the partial harvest and unharvested control compared to the complete harvest ($p = 0.01$) due to greater availability of candidate trees (fig. 4). No difference was found in snag recruitment between the partial harvest and unharvested control in 1996; therefore, the average number of snags ≥ 10 cm d.b.h. recruited across the two treatments was 5.7/ha. Recruitment and mortality of snags during the 1996 growing season resulted in a 34 percent net decrease in the number of snags in the partial harvest and an 11 percent net increase in the unharvested control (fig. 2). These two treatments contained more snags than the complete harvest (fig. 2; $p = 0.05$).

An additional 30 pretreatment snags were lost within treatment areas following the 1997 growing season. The two snags in the complete harvest were still present, while snag mortality increased 10 percent in the partial harvest and 41 percent in the unharvested control (fig. 3). No difference existed across treatments in cumulative snag mortality ($p = 0.14$), again owing to greater variability in the partial harvest (fig. 3). Greater variability (larger standard error bar) in snag mortality in the partial harvest probably was a function of harvest activities. Harvesting, either by direct contact with the equipment or dropping tree crowns into snags, would increase the likelihood of individual snags being lost between treatment replications. Spring time floods in both 1996 and 1997 also may have contributed to snag mortality, i.e., flood water and debris may have toppled weak snags. Less obstruction from remaining trees in the partial harvest may have resulted in greater water velocity and increased debris flow, further increasing treatment variability. Concurrently, smaller-d.b.h. snags in the unharvested control would be more susceptible to mortality during flooding events.

No recruitment of new snags occurred in the complete harvest following the 1997 growing season, because no candidate stems remained from the follow-up chainsaw felling treatment (fig. 4). Greater recruitment of snags again occurred in the partial harvest and unharvested control compared to the complete harvest ($p = 0.04$), but no difference existed between the former 2 treatments (fig. 4); therefore, the average number of snags ≥ 10 cm-d.b.h. recruited across these 2 treatments was 4.1/ha. Mortality of 1996 snags (first year, post-treatment new snags) was 27 and 26 percent for the partial harvest and unharvested control, respectively (data not shown). The three 1996 snags in the complete harvest were still standing following the 1997 growing season. Mortality and recruitment of snags following the 1997 growing season resulted in a 17 percent increase in the number of snags/ha in the partial harvest while snags in the unharvested control decreased by 17 percent (fig. 2).

Our review of the total number of snags by treatment (instead of treatment replication means) showed a net loss of five snags in the controls or one snag/ha/year. Therefore, two-year snag retention, or the initial number of snags plus new snags less those snags that perished, was 92 percent. Likewise, a net loss of 14 snags occurred in the partial harvest, or 2.9 snags/ha per year. Two-year snag retention was 79 percent. Based on these results, we reject our first hypothesis that greater snag recruitment would occur in the partial harvest in the short term. No differences were found between snag recruitment in the partial harvest and unharvested controls (fig. 4), although both treatments obviously recruited more snags than the complete harvest. The second hypothesis, that greater snag recruitment would occur in the long term in the unharvested control, could not be answered due to the short term (two-year) results reported in this study.

Snag dynamics are a function of species composition, stand structure, age, and stage of stand development. Disturbance also influences the rate of snag recruitment and mortality (van Lear 1996). Previous work with hardwood snags indicates that snag abundance declines in managed forests compared to unmanaged forests (Graves and others 2000, Harlow and Guynn 1983, McComb and Noble 1980). We did not find this to be the case in the present study based on short-term results comparing partial harvesting to controls. No differences were found in snag density (fig. 2), cumulative mortality (fig. 3), or recruitment (fig. 4) during the two-year study period following partial harvesting, compared to unharvested controls. We conclude that longer-term results are needed to determine if snag abundance declines in managed forests compared to unmanaged forests in bottomland hardwood ecosystems.

Snags are increasingly recognized as an important component of forest management plans. Wilson and others (2007), in a report about enhancing wildlife habitat in the Lower Mississippi Alluvial Valley, state that desired stand conditions for bottomland hardwood forests would include 15 snags/ha ≥ 25-cm d.b.h. A stand structure than contained < 10 snags was considered the target to trigger management actions to increase the number of snags. Results from out study were slightly below the desired stand structure, but within the range of 10 to 15 snag/ha – given that our minimum snag d.b.h. was 10 cm.

Practices to increase the number of snags in managed forests include designating snags or potential snags during tree marking operations, such as trees with noticeable decline (crown dieback, disease, streaks indicating lightning strikes, and suppressed trees that may not respond to release) (Harlow and Guynn 1983). Other practices could include injecting individual trees with herbicides (Hurst and Bourland 1996) or have harvesting equipment damage trees explicitly marked for the objective of creating den trees and future snags (Personal communication. Kenny Ribbeck. 2007. Biologist Program Manager, Louisiana Department of Wildlife and Fisheries, P.O. Box 98000, Baton Rouge, LA 70898-9000). More research is needed to quantify snag dynamics in bottomland hardwood ecosystems, including densities by species and size classes, longevity, and recruitment. Eventually, a snag classification system (by species), similar to the one developed for northern hardwood species in Wisconsin (Runde and Capen 1987), will aid wildlife habitat management efforts.

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Poster Session

Moderator:

KENNETH OUTCALT

USDA Forest Service

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INFLUENCE OF ESTABLISHMENT TIMING AND PLANTING STOCK ON EARLY ROTATIONAL GROWTH OF LOBLOLLY PINE PLANTATIONS IN TEXAS

M.A. Blazier, E.L. Taylor, A.G. Holley[1]

Abstract—Planting container seedlings, which have relatively fully formed root systems encased in a soil-filled plug, may improve loblolly pine plantation productivity by increasing early survival and growth relative to that of conventionally planted bareroot seedlings. Planting seedlings in fall may also confer productivity increases to loblolly pine plantations by giving seedlings more time to form root systems and accumulate nutrients before onset of droughty conditions in summer months. Potential productivity increases associated with container seedlings and fall planting may be most pronounced on well-drained sites that exacerbate the effects of drought. The objective of this study was to determine loblolly pine survival and growth in response to seedling type and planting date.

At the Texas A&M University Florey Research and Demonstration Forest near Overton, TX (32° 16' 28" N, 94° 58' 42" W), a loblolly pine plantation was established as a research site in 2002. Soil of the study site was of the U.S. Department of Agriculture Natural Resource Conservation Service Kullit series (a fine, mixed, semiactive thermic Typic Hapludults very fine sandy loam). Average annual precipitation of the site was 114 cm, and its average annual temperature was 19 °C. Seedling type and planting date treatments, each replicated three times, were applied to 0.5-ha plots in a randomized complete block design. Seedling type treatments consisted of either bareroot or container seedlings of the same family. Planting date treatments consisted of planting in either fall (October 2002) or spring (March 2003). Seedling survival, height, and volume were determined annually at the end of the first through third growing seasons. In 2005, subsamples of seedlings were excavated to determine root growth form.

Survival of the container seedlings significantly ($P > 0.10$) exceeded that of the bareroot seedlings in all years, with survival 23 percent greater than that of bareroot seedlings. Volume of seedlings planted in fall was significantly greater than those planted in spring in all measurement years, with volumes 30 percent greater than those of spring-planted seedlings. The seedling type by planting date interaction significantly influenced stand volume. In 2003, stand volume of all container seedlings was significantly greater (by 25 percent) than that of bareroot seedlings. In 2004, all fall-planted seedlings had significantly greater stand volumes than spring-planted seedlings. In 2005, fall-planted container seedlings had stand volumes significantly greater (by 49 percent) than all other treatment combinations.

The seedling type by planting date interaction significantly influenced root system architecture. Fall-planted container seedlings had greater total root system length and tap root length than fall-planted bareroot seedlings. Bareroot seedlings had greater (by 26 percent) total root system diameter than container seedlings.

These results indicate that planting container seedlings and fall planting increased early-rotation productivity on this well-drained site. Planting container seedlings improved survival rates, and fall planting increased seedling volumes. As such, the greatest increases in stand volume came from combining these treatments by planting container seedlings in fall. The survival and growth advantages of fall-planted container seedlings may have been due to their development of the deepest and most compact root systems. This root architecture may be physiologically advantageous on a well-drained site such as the one observed in this study by fostering water uptake.

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USE OF A THERMOCOUPLE-DATALOGGER SYSTEM TO EVALUATE OVERSTORY MORTALITY

Lucy Brudnak, Thomas A. Waldrop, Ross J. Phillips[1]

Abstract—In the past, it was difficult to accurately measure dynamic fire behavior during prescribed burns. Peak temperature, flaming duration, and total heat output may be directly related to first-order fire effects such as fuel consumption and vegetative mortality; however, little is known about which of these variables is most closely associated with, and therefore the best predictor of, post-burn conditions. A thermocouple-datalogger system can allow forest managers and scientists to record data related to maximum temperature, heat pulse duration, and total heat output at any location within a prescribed burning treatment area over a user-defined time period. The advantage of this type of system is its ability to evaluate the rate of spread and intensity of a prescribed burn, and to relate those spatial variabilities to short- and long-term effects such as tree mortality. Regression equations of fire attributes and overstory mortality indicated that immediately following the first fire, flaming duration and average flame temperature together explained 43 percent of the mortality observed. After two years, average temperature alone showed the strongest relationship to mortality but only accounted for 24 percent of the variance. Overstory mortality was lower after the second burn, with total heat output explaining 45 percent of model variation.

INTRODUCTION

As the effects of decades of fire suppression become increasingly apparent, it is important for forest managers and researchers to understand the relationships between fire, fuels, and vegetation. The success of a prescribed burn is often judged by the extent of fuel load reduction and by the direct and indirect impacts of the fire on vegetative species of interest, e.g., *Quercus* spp. (Artman 2005, Freckleton 2004). Also of interest is the ability to predict fire characteristics such as flame height and rate of spread from a given fuel complex; although fire models are now proving useful in this area of research, technological limitations have previously made such estimations difficult (Anderson 1969). Thermocouple-datalogger systems have helped to overcome these limitations to some extent, as they can be installed in areas with known fuel loads and species compositions; this allows direct correlations to be made among pre-burn site attributes, fire characteristics, and post-burn site conditions. Additionally, the effects of specific fire characteristics on forest dynamics such as post-burn mortality of target species can be more clearly differentiated.

METHODS

Site Description and Study Design

The Southern Appalachian Mountains site of the National Fire and Fire Surrogates (NFFS) Study is located on the Green River Game Lands in Polk County, NC (GR). The overstory of this area is primarily oak and hickory species (*Quercus alba, Q. coccinea, Q. prinus, Q. rubra, Q. velutina, Carya alba, C. glabra, C. pallida*), with yellow pines (*Pinus echinata, P. pungens, P. rigida, and P. virginiana*) also present along exposed ridges and white pine (*P. strobus*) in the protected cove areas.

The study design at each NFFS site is a randomized complete block, with three replications of four treatments. GR treatments consisted of a control, burn-only, mechanical-only, and mechanical+burn. Treatment areas contain 38 to 40 plots arranged on a 50-m grid spacing; fuels were measured in each plot along three 20-m transects, following Brown's (1974) planar intersect method. In addition, overstory, shrub, herbaceous vegetation, and regeneration data were collected at ten 0.1-ha plots per treatment. The burn-only and mechanical+burn treatments were burned twice- first in spring 2003 and again in spring 2006. Prior to burning, 12-inch stainless steel Type K thermocouples and dataloggers were installed at the center of each plot, co-located with the center fuel transects. For the duration of the fires, dataloggers recorded temperature information every 1.5 seconds. Using these data, values for maximum and average temperatures, flaming duration, and time above 60 °C (the temperature at which vascular cambium cell mortality occurs (Dickinson 2004)), and total heat output were calculated. Correlations and regressions between these fire characteristics and post-treatment overstory mortality were performed on transformed variables.

RESULTS

2003 Burn

The first burn at this study site took place in March 2003. In the burn-only treatment, the fire in all blocks was low-intensity and patchy in nature, whereas complete burn coverage was achieved in the blocks in the mechanical+burn treatment area. Overall maximum temperature for the spring 2003 burn was 256 °C, with an average temperature of 106 °C. Mean duration of the flame peak at a thermocouple was 8.10 minutes, and the mean heat output for this fire was 13.73 MJ/kg. Four months after this burn, mean overstory mortality was 1.95 m^2/ha with average temperature and flaming duration showing the strongest relationship to mortality; together they accounted for 43 percent of the variation in the statistical model. Two years later, mean overstory mortality had reached 2.14 m^2/ha. Average temperature was the strongest predictor of mortality at this point, but it accounted for only 24 percent of the variance.

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2006 Burn

The second burn at Green River was applied in March 2006, with lower overall fire intensities than in 2003. Maximum and average temperatures for this fire were 189 °C and 20 °C, respectively. Mean duration of the flame peak was longer, at 12.33 minutes, but mean heat output was slightly lower than in the 2003 fire, at 10.13 MJ/kg. Four months after the fire, mean mortality was 1.09 m^2/ha. Total heat output was the best predictor of overstory mortality after the second fire, explaining 45 percent of the variation.

Oak Mortality

First-order oak mortality did not follow the expected pattern of greater mortality at higher temperatures (fig. 1). However, many oaks died in the second or third year after burning. Two-year post-burn results better approximate the anticipated trend, as does mortality one year following the second burn. Maximum temperatures above 300 ºC produced a sharp increase in oak mortality between 2003 and 2005. It is likely that the temperatures which the oaks endured during these two burns are influential factors in this delayed response. Use of the thermocouple-datalogger system allowed us to approximate the temperature and duration of fire to which individual trees were exposed, thereby improving our confidence in the relationship between these variables and mortality.

DISCUSSION

The importance of both fire temperature and flaming duration to potential overstory tree mortality was evident shortly after the first prescribed burn in 2003. Our results agree with those of Jones and others (2006), who developed a predictive model of tree mortality based on the relationship between fire-induced heating in tree stems and the tissue necrosis that often results from exposure to such heat. The model accounts for the rate-dependent characteristics of both fire temperature and heating duration with respect to potential fire-induced tree mortality. The value of considering such factors when examining fire's relationship to mortality is borne out by the accuracies observed in the testing of their model; they were able to predict mortality and survival of both hardwood and softwood species with 75 to 80 percent accuracy. Ansley and others (1998) found peak fire temperature and fire duration to be important factors in predicting mortality in honey mesquite (*Prosopis glandulosa* Torr.) communities, and the effects of both variables increased with thermocouple height. Our results and those of others reflect the importance of considering a variety of characteristics when examining fire-induced tree mortality and incorporating the rate-dependent aspects of fire behavior into considerations of vegetative responses. It is evident that the mechanisms by which fires act to damage and destroy plant tissues are more complex than may simply be attributable to flame temperature alone; lower-intensity fires may be just as detrimental to the survival of overstory species as high-intensity burns, provided the flaming duration is long enough to effectively destroy cambial tissues.

Overstory mortality dynamics were different at two years post-burn than immediately following treatment. Delayed mortality continued and slightly increased well into 2005, which is consistent with other research suggesting that most fire-induced mortality occurs within the first two years following burning (Loomis 1973, Regelbrugge 1994). Other studies in eastern forests have reported similar results, citing time-dependent and fire intensity-dependent differences in overstory tree mortality following wildfire (Groeschl and others 1992). This reinforces our observations about the responses of mixed hardwood forests generally, and oak species in particular, to the presence of fire. Recognizing the importance of fire intensity and time since burning to fire-induced hardwood mortality is key if we hope to fully understand and accurately predict the responses of particular species of interest to such disturbances.

Following the 2006 burn, total heat output alone showed a significant relationship to overstory mortality. Kobziar and others (2006) found that fireline intensity, which is itself a factor used in the calculation of total heat output, was important to predicting post-fire mortality of conifer species in the Western United States. However, in both pine and mixed hardwood forests in the Eastern United States, total heat output was judged a better correlate of stem surface heat flux (Wade 1993, Bova and Dickinson 2005). The greater predictive power of total heat output over fire intensity alone highlights the usefulness of thermocouple-datalogger

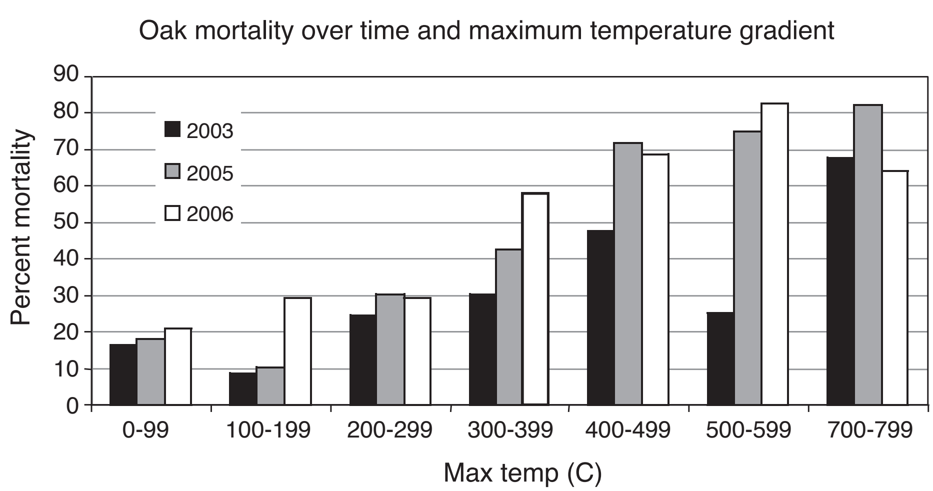

Figure 1—Percent overstory oak mortality across a gradient of time and maximum temperature.

systems in prescribed fire and wildfire research. These systems make the vital time dimension of fire behavior more accurate and more accessible to researchers, providing a wider range of factors with which to understand the dynamic interactions between fire and the ecosystem responses it generates.

CONCLUSION

The capability of the thermocouple-datalogger system we employed to capture the dynamic nature of fire characteristics over time helped us to elucidate some interesting trends at the Southern Appalachian Mountains site of the National Fire and Fire Surrogates Study. While our regression equations were only able to explain approximately 1/4 to 1/2 of the variation observed in this study, we nevertheless gained some useful insights about the changing nature of fire effects in this eastern mixed hardwood forest. Fire temperature, duration, and total heat output are all important factors in understanding the ecological impacts of fire disturbance on vegetation, but their relative importance varies over time and with the changing nature of the post-fire overstory cohort. The thermocouple-datalogger system used in this study proved to be useful and effective tools for discerning the complex relationships between fire and the environments it influences.

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DEVELOPMENT OF A SHORTLEAF PINE INDIVIDUAL-TREE GROWTH EQUATION USING NON-LINEAR MIXED MODELING TECHNIQUES

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Abstract—Nonlinear mixed-modeling methods were used to estimate parameters in an individual-tree basal area growth model for shortleaf pine (*Pinus echinata* Mill.). Shortleaf pine individual-tree growth data were available from over 200 permanently established 0.2-acre fixed-radius plots located in naturally-occurring even-aged shortleaf pine forests on the USDA Forest Service Ozark and Ouachita National Forests in western Arkansas and southeastern Oklahoma. The plots were established during the period from 1985 to 1987. Two subsequent re-measurements were used in this study, resulting in a total of three measurements and two growth periods. The equation can be used to predict the annual basal area growth of individual shortleaf pine trees as a function of individual tree basal area, forest stand basal area per acre, stand age, and the ratio of individual tree d.b.h. to quadratic mean stand d.b.h. The mixed-model procedure used random plot-level effects associated with individual tree basal area to account for correlation among individual trees located on the same plot. This resulted in improved fit statistics compared to a similar model fitted using nonlinear ordinary least squares.

INTRODUCTION

Shortleaf pine (*Pinus echinata* Mill.) has the widest geographical distribution of any southern pine, yet has received less attention in terms of growth modeling than other southern pines. Most growth and yield information for southern pine prior to 1985 was based on full stocking assumptions. Lynch and others (1999) used re-measured plot data from over 200 permanently established shortleaf pine growth study plots to develop a distance-independent individual-tree simulator for naturally-occurring shortleaf pine forests. This simulator utilized an individual tree basal area growth equation in which parameters were estimated by ordinary least squares (OLS). The OLS procedure performed satisfactorily in tests but does not fully account for correlations among individual sample trees located on the same sample plot. Trincado and Burkhart (2006) suggested that the assumption of correlated errors could be relaxed in the presence of a tree-level random effect in a stem profile curved fitted to data consisting of multiple stem measurements on a sample of individual trees. Here we wish to use a plot-level random effect to help account for correlations among individual trees located on the same plot. The development of mixed-modeling estimation techniques (e.g., Gregoire and others 1995, Hall and Bailey 2001) and the availability of additional plot measurements not used in the 1999 analysis provide the opportunity to obtain new estimates for the parameters of a basal area growth equation using mixed modeling methods.

METHODS

Lynch and others (1999) estimated the following nonlinear model parameters using OLS:

$$G_i = \frac{b_1 B_i^{b_2} - \left(b_1 B_i / B_M^{1-b_2}\right)}{1 + \exp(b_3 + b_4 B_s + b_5 A + b_6 R_i + b_7 B_i)} \qquad (1)$$

where G_i is annual basal area growth (square feet) of tree i; B_i is basal area (square feet) of tree i; A is stand age; R_i is the ratio of quadratic mean stand diameter to the d.b.h. of tree i; B_s is stand basal area (square feet per acre); B_M = 7.068384 square feet (the maximum expected basal area for a shortleaf pine in managed stands); and b_1, b_2, ….., b_7 are parameter estimates. Testing of the tree-level independent variables in the equation above indicated that the most promising independent variable with which to associate a plot-level parameter was individual tree basal area. This modification resulted in a mixed-effects model having a random parameter associated with individual tree basal area. The “mixed model” is a result of fixed parameters, which are constant for all plots, and random parameters, which vary by (randomly chosen) plots.

RESULTS AND CONCLUSIONS

Nonlinear mixed modeling techniques were used to estimate parameters in the individual-tree basal area growth model for shortleaf pine. The NLME procedure with SPLUS software described by Pinheiro and Bates (2000) was used to obtain the parameter estimates. Fit statistics indicated improved fit for the mixed-effects model compared to a more traditional approach that did not include mixed effects. Thus, mixed-model estimation procedures appear to be advantageous for individual tree basal area growth equations where data are obtained by re-measured plot sampling.

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BIOMASS AND NITROGEN DYNAMICS OF FOUR PLANTATION TREE SPECIES RECEIVING IRRIGATION AND FERTILIZATION

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In addition to fiber and wood production, there has been renewed interest in using forest biomass for energy production through both direct combustion and through technologies to produce liquid fuels from wood. In addition, growth and productivity of forests have important potential implications in terms of carbon sequestration and carbon credits because growth is directly related to carbon removal from the atmosphere. To better meet these current and future biomass related objectives, there are several important issues that need to be better understood related to growth potential, biomass partitioning to different aboveground stand components, and nitrogen demand and partitioning among stand components.

Our objectives were to: 1) determine the growth potential of four fast-growing species that are suitable for plantation culture, i.e., loblolly pine (*Pinus taeda*), slash pine (*Pinus elliottii*), sweetgum (*Liquidambar styraciflua*), and sycamore (*Platanus occidentalis*); 2) quantify the effect of resource availability (water and nutrients) on aboveground biomass accumulation and partitioning; and 3) quantify the effect of resource availability on aboveground nitrogen accumulation and distribution.

The study area was an 11.7-ha study site established in 1997 near Mt. Pleasant, GA by Plum Creek Inc. The sandy soil is a mesic, coated Aquic Quartzipsamments (Klej series). Treatments were laid out in three blocks (n = 3). Nutrient and water additions were applied during each growing season beginning year one. Treatments consisted of control (C), 3.05 cm-water/wk (I), 3.05 cm-water/wk + 57 kg-N/ha/yr (I + 57N), 3.05 cm-water/wk + 85 kg-N/ha/yr (I + 85 N), 3.05 cm-water/wk + 114 kg-N/ha/yr (I + 114N). All nutrient and water additions were evenly applied via drip irrigation throughout the growing season. The fertilization mix also included P, K, and micronutrients. Measurements were taken during the sixth growing season. Following the sixth growing season, three trees per plot were harvested and stem volume and dry biomass were determined. Bark and wood were separated. Total branch biomass was determined for the same harvest trees. Stem and branch biomass were scaled to the plot basis using regressions between dbh^2*height and biomass. Treatments did not affect these relationships. Leaf biomass was determined from periodic collections of litter in five 1-m^2 traps per plot. Nitrogen concentrations of stem wood, stem bark, branch wood, and branch bark were determined at the time of the harvest. Foliar N was measured based on mean of several growing season samples. Nitrogen contents were calculated by multiplying the biomass component by the corresponding N. For all analyses, the experimental unit was the plot-level estimate of biomass, nitrogen concentration, or nitrogen content. For all variables, differences due to fertilization were evaluated by comparing treatments receiving water additions (i.e., I, I+57N, I+85N, and I+114N). The effects of irrigation were evaluated by comparing the control (C) and irrigated only (I).

Compared to the control treatment, irrigation and fertilization increased stem wood biomass for sweetgum (1,860 to 27,600 kg/ha) and sycamore (3,800 to 37,400 kg/ha) more than for loblolly pine (24,410 to 42,150 kg/ha) and slash pine (14,000 to 26,660 kg/ha). In addition, irrigation and fertilization increased growth efficiency (stem growth per unit of foliage) of the hardwood stands while partitioning within the pine stands did not change. Fertilization increased foliar N in sweetgum (1.4 to 2.0 percent) and sycamore (1.5 to 2.0 percent) and also increased nitrogen use efficiency (stem wood growth per unit of foliar N) in these species. Fertilization did not affect foliar N dynamics of the pines. However, because of the large increases in stand biomass with irrigation and fertilization, total nitrogen content of the aboveground biomass increased for all species (154 to 252 kg-N/ha for loblolly pine, 121 to 205 kg-N/ha for slash pine, 44 to 238 kg-N/ha for sweetgum, and 45 to 203 kg-N/ha for sycamore). These results quantify the potential growth rate and nitrogen demand of four fast growing species and indicate that growth, biomass partitioning, and foliar N of sweetgum and sycamore are more responsive to resource availability than for loblolly and slash pine.

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CASE STUDY TO EXAMINE THE EFFECTS OF A GROWING-SEASON BURN AND ANNOSUM ROOT DISEASE ON MORTALITY IN A LONGLEAF PINE STAND

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Abstract—A case study of a growing-season burn in a longleaf pine (*Pinus palustris*) stand affected by annosum root disease was conducted at Savannah River Site, SC. The project utilized a longleaf pine stand from a 1995 evaluation of a stump applicator system. The Tim-bor® (disodium octaborate tetrahydrate) and no stump treatment blocks (NST) were divided into sections for a burn treatment. Prior to the burn, woody debris was added to selected plots in each of the burn areas to simulate a midstory cut of hardwoods. The fire applied in April 2003 was designed to mimic spot ignitions of a plastic sphere dispenser (PSD) machine. In 2003 to 2005, the percent increase of dead trees per acre with annosum root disease was greater in the burn areas than in the no burn areas in both the Tim-bor® and the no stump treatment blocks. Mortality related to fire/heat damage was greater in the midstory plots of the Tim-bor® block than in the NST block. Annosum root disease was confirmed in 256 trees out of 589 total dead trees, but caused less then 10 percent timber loss over 10 years. Mortality related to the burn resulted in 86 dead trees, and losses due to an ice storm resulted in 56 dead trees. Other timber losses occurred from mechanical damage, lightning, fusiform rust/wind, and no primary cause determined.

INTRODUCTION

Prescribed burning in longleaf pine (*Pinus palustris*) stands is an important tool for managing hazardous fuels (Outcalt and Wade 2004), regenerating longleaf pine (Croker and Boyer 1975), and suppressing other tree species (Hille and Stephens 2005). Longleaf pine is adapted to frequent low intensity fires (Chapman 1932); however, the use of prescribed fire in longleaf pine is not without risk. There have been individual cases of high mortality in longleaf pine stands after a prescribed burn (Sullivan and others 2003, Varner and others 2005). Severe fire can damage pines through crown scorch, meristem damage, stem char, vascular damage and root damage (Varner and others 2005). Mortality of longleaf pine has been correlated with the severity of the burn (Sullivan and others 2003), and combustion of excessive litter resulting in root and/or cambium damage (Brockway and others 2005, Varner and others 2005).

A prescribed burning study at the Savannah River Site (SRS), SC, found that soil heating and surface consumption of duff was correlated to mortality of mature longleaf pine (Sulivan and others 2003). This study also found annosum root disease, caused by *Heterobasidion annosum*, was present and associated with root infections and mortality (Otrosina and others 2002, Sullivan and others 2003). The physiological stress resulting from fire damage can render southern pines more susceptible to insects and disease (Hanula and others 2002, Sullivan and others 2003, Varner and others 2005), which can lead to mortality. There has been little research on the possible interaction between annosum root disease and prescribed fire. Annosum root disease development occurs over a 10-year period in southern pine stands (Tainter and Baker 1996) and its impact can be underestimated when surveys are only a couple of years in duration. Infection of a stand by *H. annosum* can also be highly variable and not evenly distributed. Long-term annual monitoring of dead and dying trees for the presence of root disease is needed to examine possible interactions of annosum root disease and prescribed fire.

The primary objective of this case study was to quantify tree mortality in a longleaf pine stand with annosum root disease before and after prescribed fire. A longleaf pine stand that had once been part of a study on the SRS provided the initial long-term annual monitoring of annosum root disease. This 89-acre stand was the only remaining stand from a 1995 stump applicator system study for suppression of annosum root disease. The stand had been monitored from 1996 to 1999 for root disease and other causes of mortality within the treatments. The treatments consisted of Tim-bor® (disodium octaborate tetrahydrate), *Phlebiopsis gigantea* and NST (No stump treatment) blocks. The first four years data on the site indicated that Tim-bor® had excluded *H. annosum* from treated stumps and that annosum root disease was present in the NST (No stump treatment) block. The *Phlebiopsis gigantea* stump treatment failed due to applicator error (20 percent stumps not treated), therefore only the Tim-bor® and NST blocks where used for the case study.

Midstory cuts, where hardwoods are chainsaw felled before burning, are common practices in restoring longleaf pine stands on the SRS (Barton and others 2005). Midstory cuts increase the fuel load in a stand, which can be a contributing factor to increased burn severity under some conditions. Forest Management at the SRS was interested in obtaining information on temperatures generated at the upper layer of mineral soil with different fuel levels and weather conditions.

METHODS

The longleaf pine stand (Lat. 33°21'30", Long. 81°30'0") selected for this case study had a soil type of Blanton sand and a site index of 70. The stand was established in 1955 and thinned to a basal area of 72 square feet in 1995. The original stump treatments (NST, Tim-bor®, *Phlebiopsis*

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gigantea) had been applied in randomized blocks within each of three longleaf pine stands during the 1995 thinning. Only the Tim-bor® and NST treatment blocks were used in this case study. The Tim-bor® block was 36.56 acres and the NST block was 28.47 acres. A prescribed burn treatment (ignited April 2003) was imposed on of each treatment block (Tim-bor® 11.89 acres; NST 11.12 acres).

A 100-percent survey of tree mortality was conducted in the Tim-bor® and NST blocks each fall from 1996 to 1999, and was continued from 2001 to 2005. All dead trees were assessed yearly for root disease using the two root method (Alexander and Shelly 1974). Symptomatic root segments with resin-soaking or white-stringy-rot were cut up and placed on a selective media for basidiomycetes (Russell 1956). All dead trees confirmed to have *H. annosum* were mapped with GPS (global positioning system).

In 2001, the 63 variable plots (10-factor prism) in the blocks from the previous stump project were used to establish 0.10-acre fixed plots. The plot centers were established on a 2 chain (66 feet) x 2 chain grid. All trees within the fixed plots were measured for d.b.h. within 0.1 inch. The boundaries and acreage of the individual blocks and burn treatment areas were measured with GPS. The number of trees estimated for each area was based on the fixed plot measurements and the acres in each treatment area.

Three plots within each burn treatment area were systematically selected along a centered transect (Northeast to Southwest) to simulate midstory cuts. In August and September 2001, small trees (less than 5 inch d.b.h.) in and around the 0.1-acre midstroy plots were cut and added to a fuel depth of 1.5 to 2.5 feet on top of the natural fuel load, which averaged 0.9 inches litter and 1.5 inches duff. Thermometers (maximum temperature) were placed at 0.5 and 2 inches below the duff within and outside the midstory plots. Campbell Scientific Microloggers were also utilized in the centeral midstory plot of each burn area to determine ground temperature change over time under high fuels and natural fuels. The microloggers were placed below ground in a styrofoam container on the east side of the plot. The probes used were high temperature quick-disconnect thermocouple (grounded K) on 12 feet of insulated thermocouple wire duplex (insulated K; Omega Engineering Inc.). Each micrologger had two sets of temperature probes in the midstory plot and two sets of probes outside the plot. Each set of probes consisted of a probe at 0 inches and another at 2 inches below the duff. Two sets of probes were located 6 to 10 feet apart within the midstory plot and the other two sets were placed outside the plot at 6 to 10 feet apart.

Prescribed burns had been applied to the stand every 3 to 5 years through the winter of 1996. No fire related mortality occurred following the 1996 prescribed fire. The stand was not burned again until the prescribed treatment burn was ignited on April 24, 2003. The burn technique used was spot fires applied in strips with drip torches designed to mimic spot ignitions of a plastic sphere dispenser (PSD) machine. The burn began at 10:44 a.m. in the Tim-bor® block moving southeast into the NST block at 12:15 p.m. At initiation of the burn it had been 5 days since rain (0.6 inch), KBDI was 93, and the lowest 10 hour fuel stick moisture was 9 (SavRiv 383101). During the burn relative humidity ranged from 35 to 41 percent and air temperature ranged from 70–80 °F. Wind movement within the stand was 0 mph when the burn started and steadily increased to 4 mph by 14:00 in the afternoon. The duff and litter consumption was noted when thermometers were removed. The height of bole char was recorded on trees within plots.

In November 2005, increment cores were taken from 3 live trees in 3 plots of each burn and stump treatment areas. Cores were taken on the side of the tree facing the center of the plot. Sample trees were selected based on diameters closest to 11.5 inches d.b.h. within the first three quadrants. All trees measured for radial growth were codominant. Radial growth was measured for each year from 1996 through 2005.

RESULTS

The highest temperature recorded by the maximum thermometers was 88 °F. The temperatures recorded by the maximum thermometers were similar to the recorded temperatures from the Campbell temperature probes from the Tim-bor® treated block (fig. 1). One of the Campbell temperature probes (0 inches, NST block) recorded a temperature of 169 °F (fig. 2), which was likely due to that probe's location under a log. Fuel was not consumed down to the mineral soil, with the exception of one plot in the NST block (the northwest corner).

The locations of dead trees with annosum root disease before and after the April 2003 burn are shown in figure 3. *Heterobasidion annosum* was the most common primary damaging agent over the entire 10 year period, representing 44 percent of 589 dead trees. Although there was an increase in the percentage of mortality with *H. annosum* in the burn treatments (fig. 4), most of the post-burn annosum root disease occurred at locations where the disease had been active prior to burning. The second and third causes of mortality included fire/heat at 14.6 percent (12.5 percent excluding the midstory plots), and an ice storm (January 26-30, 2004) at 9.5 percent. Other causes included mechanical (logging), lightning, fusiform rust/wind, or no cause determined (28 percent). *Leptographium* spp. were found in roots of 1.7 percent of dead trees with no primary damaging agent determined. *Leptographium* species were associated with 1.2 percent of the annosum root disease mortality, 4.7percent of the fire mortality, and 8.9 percent of the storm-related mortality. The majority of *Leptographium* species isolated appeared to be *L. procerum* and *L. terebrantis*. One isolate of a *Leptographium*-type species, taken a root predominantly colonized by *H. annosum*, was later identified as *Ophiostoma huntii* (pers. comm., Dr. Thomas Harrington, Dept. of Plant Pathology, Iowa State University, Ames IA 50011).

Galleries and pitch tubes characteristic of *Dendroctonus terebrans* and *Ips* spp. bark beetles were found in almost all dead and dying trees. *Dendroctonus terebrans* damage was also documented in a few live trees with bark char in the midstory plots that survived to 2005. *Dendroctonus terebrans* and *Ips* spp. bark beetles are commonly associated with

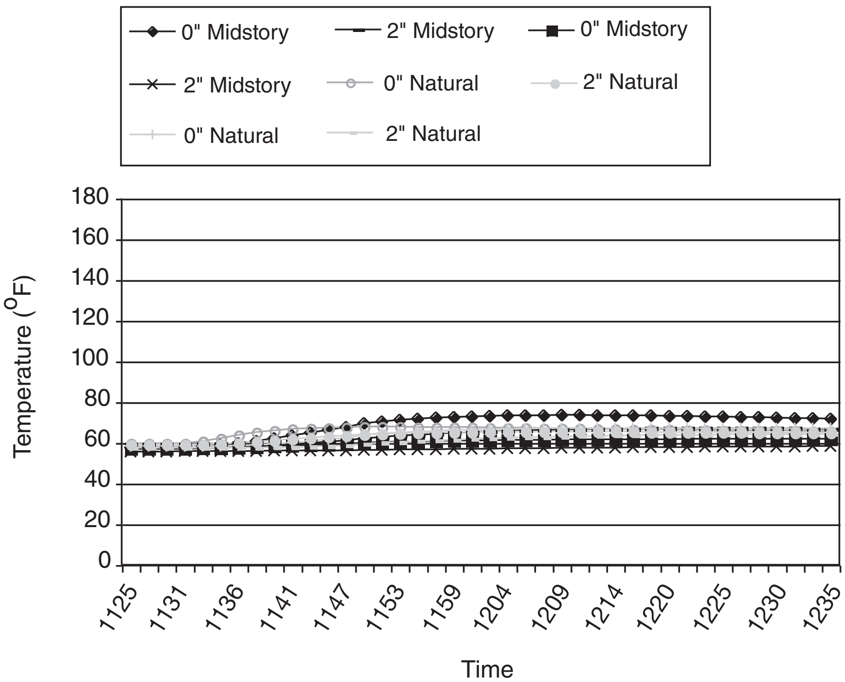

Figure 1—Temperatures (°F) in the block treated with Tim-bor® during a spring burn from probes at 0 and 2 inches below the duff in a plot with added midstory fuel and a an adjacent natural fuel plot.

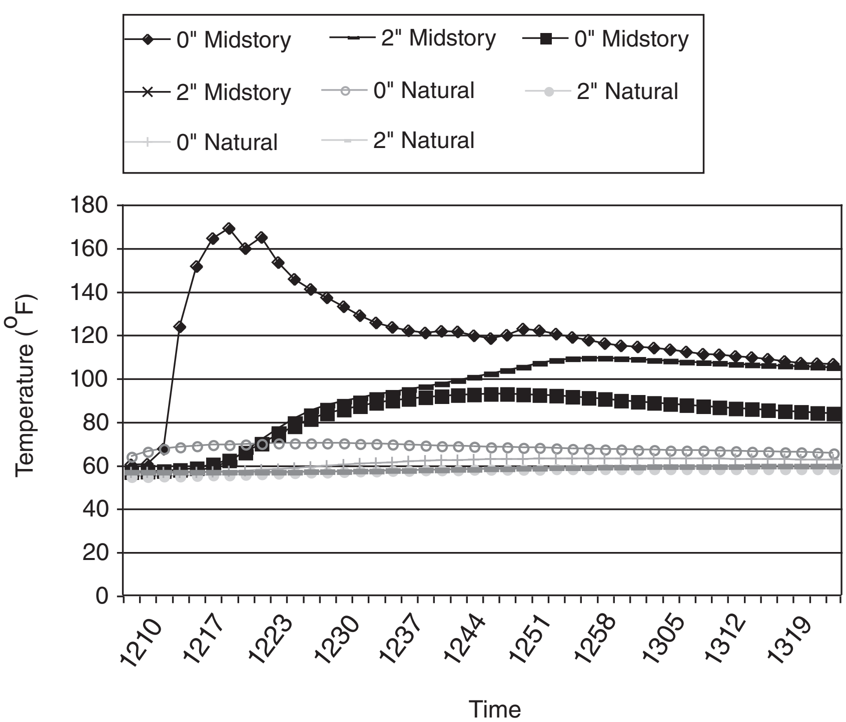

Figure 2—Temperatures (°F) in the No Stump Treatment block during the burn from probes at 0 and 2 inches below the duff in a plot with added midstory fuel and in an adjacent natural fuel plot.

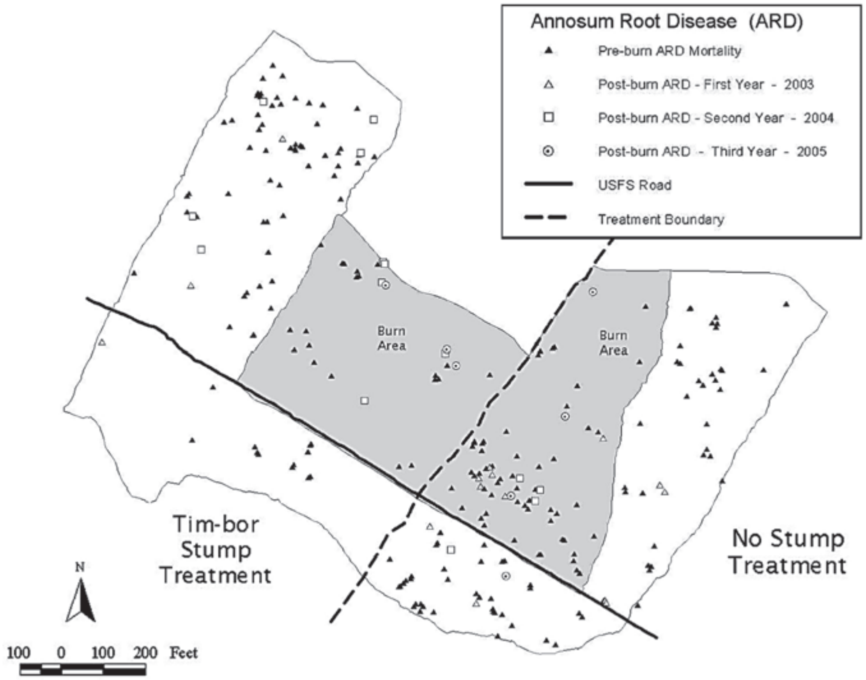

Figure 3—Location of individual trees with annosum root disease pre- and post-burn in different treated areas of longleaf stand on the Savannah River Site, SC.

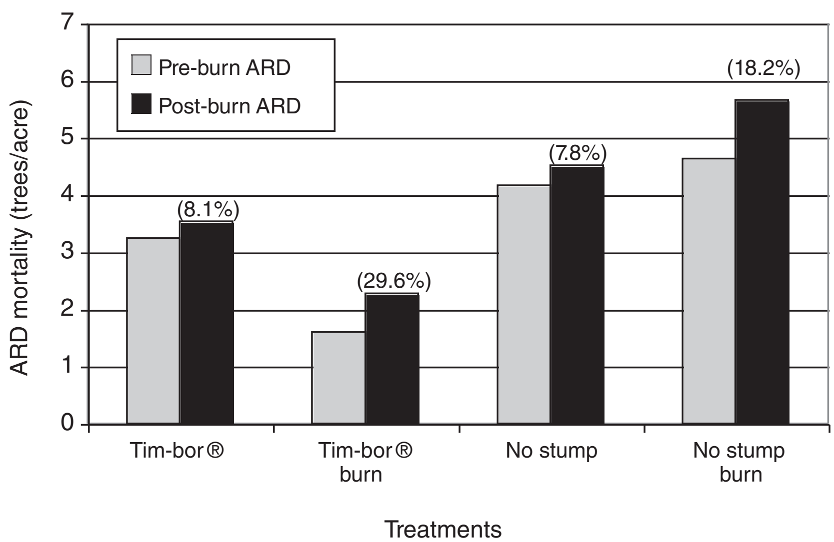

Figure 4—Annosum root disease (ARD) mortality before and after burning by stump and burn treatments (percent increase).

damaged and dying trees (Coulson and Witter 1984) and are not considered a primary damaging agent in this study.

Mortality was substantially greater in the Tim-bor® midstory plots (fig. 5). The height of bole char was also observed to be greatest on the trees in the Tim-bor® midstory plots (average 12 feet) than in the NST midstory plots (6-8 feet on one side). Bark char was 1 to 2 feet high in plots with natural fuels. Only 6.5 percent of fire-damaged trees were dead by the fall sampling in 2003. The majority of the mortality related to fire (83 percent) occurred in 2004. In 2005, an additional 10.5 percent of fire damaged trees died.

The percent of total mortality (excluding midstory plots) by different treatment areas from 1996 to 2004 is shown in figure 6. The loss of longleaf pine from the fall of 1996 to 2005 was greatest (12.7 percent) in the burn-NST area. The average annosum root disease mortality was higher in the NST block than in the Tim-bor® block, with the exception of the NW corner of the Tim-bor® block where a logging deck was located during the 1995 thinning.

The average annual growth rate of the trees in different burn plots indicated that growth slowed initially after the burn (fig. 7). By the second growing season, the burned plots with normal fuel loads had recovered. The surviving trees in the midstory plots appear to be recovering from the burn by the third growing season. The average growth rate in the individual plots indicates that growth increased in the third year in all plots except in one midstory plot in the NW corner of the NST block (data not shown).

DISCUSSION

This case study is unique in that 100 percent of the mortality was evaluated for root disease over a 10-year period. The most common primary causal agent of mortality was annosum root disease; however, the loss to the residual stand in all treatment areas from this disease over 10 years was under 10 percent. This relatively low level of disease response is not unexpected given the lower susceptibility of longleaf pine to annosum root disease (Hodges 1974).

The finding of annosum root disease in the Tim-bor® block by 2001 was unexpected given that the stump treatments were successful and mortality related to annosum occurred in the first 4 years was negligible. However, it has been well documented that stump treatments do not restrict infection to the roots or residual trees damaged by equipment (Hendrix and Kuhlman 1964, Hodges 1970, Kuhlman 1969, Rishbeth 1959). The higher level of annosum root disease surrounding the logging deck in the NW corner was likely due to heavy equipment damage to roots and trees that would allow *H. annosum* to become established in the stand despite effective stump treatment.

Heterobasidion annosum was a relatively minor factor in the mortality that occurred after the April burn. Mortality associated with annosum root disease increased in the burn areas, but most of this mortality was adjacent to locations where the disease occurred prior to the burn. Prescribed fire can have a negative effect on longleaf pine growth (Boyer 1987, Sayer and Haywood 2006), and this stress combined with annosum root disease would be expected to accelerate tree mortality.

The high occurrence of fire-related mortality found in the artificially created midstory plots of the Tim-bor® block indicates that the higher fuel load was an important factor. The damage appeared to be related to above ground temperatures, since the below ground temperatures remained low according to most of the temperature probes and thermometers. The one probe that did record lethal temperatures was positioned under a 4-inch d.b.h. log. This result indicates that there could be zones of lethal temperatures among larger fuels, which could result in localized damage to roots.

The low temperatures at 0 and 2 inches below the duff layer were likely due to the high moisture saturation of the duff and soil, which has been shown to greatly reduce surface soil temperatures (Frandsen and Ryan 1986) and can help to protect the fine roots and cambium at the base of the tree (Brockway and others 2005). During this case study, no measurement was made of above-ground temperatures, or cambium damage at the butt of trees, so it is unclear if damage occurred to the cambium in the midstory plots. Bole char height may not be considered as good as percent crown loss for predicting mortality in southern pines (Outcalt and Wade 2004); however, bole char has been correlated with greater mortality of southern (Hanula and others 2002) and western pines (McHugh and Kolb 2003, Swezy and Agee 1990, Thies and others 2006) and could be considered an analog of crown damage (Wade and Johansen 1986). In this

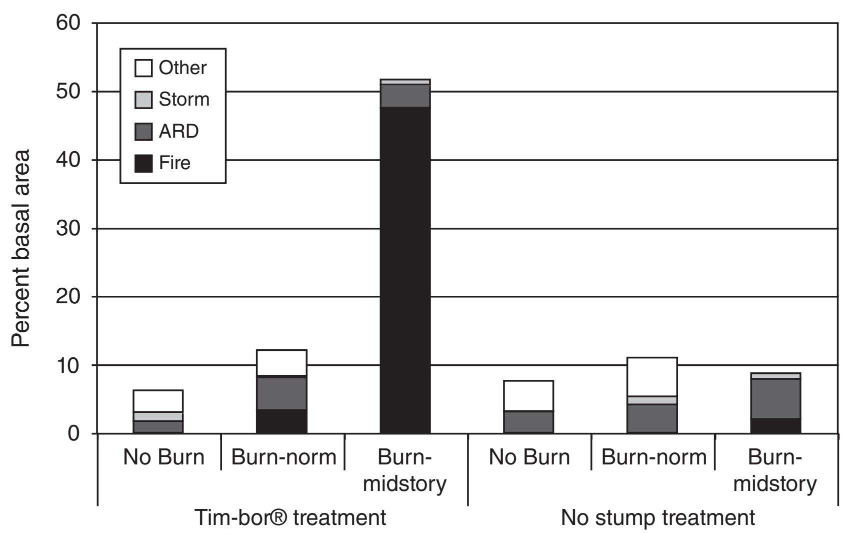

Figure 5—Percent basal area lost by primary cause within fixed plots from 1996 to 2005.

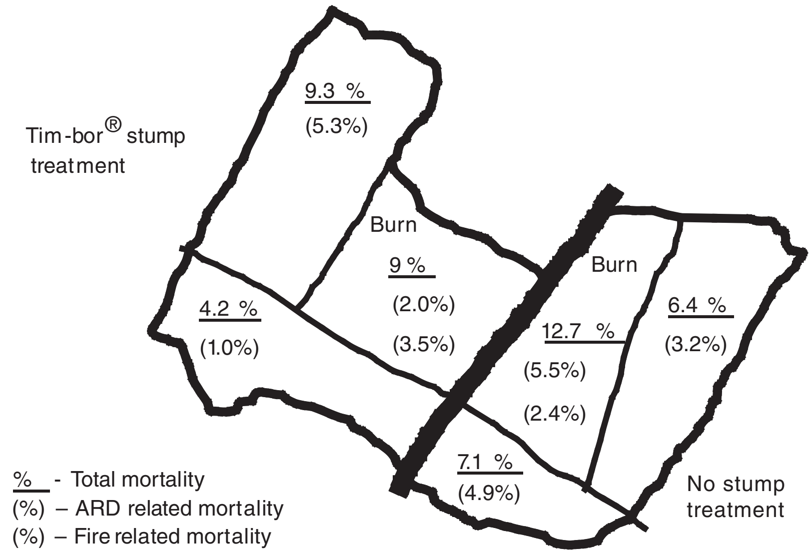

Figure 6—Percent of total tree mortality (excluding the midstory plots) by treatment block from 1996 to 2005.

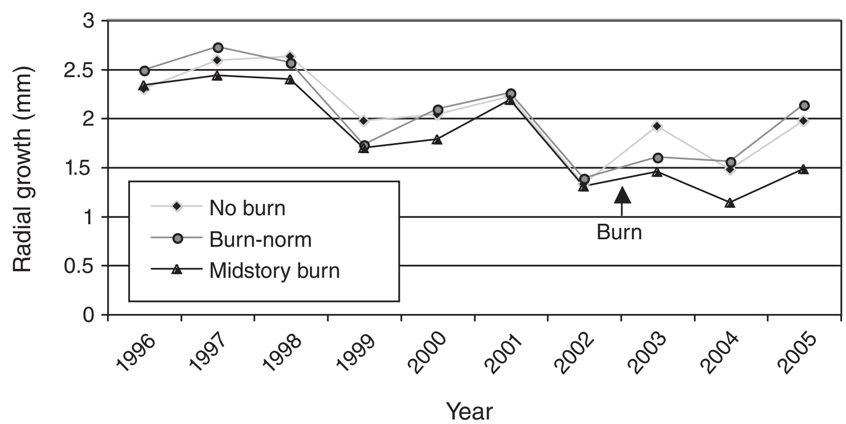

Figure 7—Average radial growth of surviving trees within different treatment plots of a longleaf stand on the Savannah River Site, SC.

case study, the plots with the most mortality were observed to have the highest bole char.

A factor that may have influenced mortality in the Tim-bor® and NST midstory plots was the wind speed and movement of heat in these blocks. During the first half of the burn in the Tim-bor® block, the wind speed in the stand was 0 MPH, which would allow heated air to rise directly into the crown (Wade and Johansen 1986). The increase in wind speed in the latter part of the day should have assisted dissipating the heat in the NST block (Wade and Johansen 1986). The three NST midstory plots also had nearby openings in the canopy (a clear-cut, skid trail, annosum root disease center) which would have allowed for greater air movement.

In many studies involving fire damage, mortality of mature trees largely occurs in the first 2 years after the burn (McHugh and Kolb 2003, Outcalt and Wade 2004, Thies and others 2006). The mortality related to fire damage in this case study occurred primarily within the first year and a half after the burn. By the second or third growing seasons after the burn, the residual trees in the burn plots appeared to recover annual radial growth rates similar to the unburned plots. Only one plot was negative for radial growth in the third year. This plot was located in the NW corner of the NST block where all fuel was consumed to the mineral soil, a factor that could be linked to higher mortality (Outcalt and Wade 2004). Annosum root disease was also present in this plot and could be a reason for a continued decline in annual growth.

The data presented in this paper only provides a single case study on the interaction of one spring burn and annosum root disease on mortality. The conditions under which prescribed fire is applied can affect the severity of the burn, and under different conditions (fuel loads, weather, duff moisture, wind speed, etc.) results can vary. The results of this case study indicate that fuels and burn conditions had a greater influence on catastrophic loss than annosum root disease. Although there was an increase in annosum root disease loss in burned areas with natural fuels, the losses appeared to be limited to trees already infected by the disease.

ACKNOWLEDGMENTS

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GROWTH RESPONSE OF DOMINANT AND CO-DOMINANT LOBLOLLY PINES TO ORGANIC MATTER REMOVAL, SOIL COMPACTION, AND COMPETITION CONTROL

Robert Eaton, William Smith, and Kim Ludovici[1]

Abstract—The Long Term Soil Productivity (LTSP) experiment is a U.S. Forest Service led effort to test the effects that organic matter removal, soil compaction, and competition control have forest soil productivity, as measured by tree growth. A replicated experiment was installed on the Croatan National Forest, NC, in winter 1991 and loblolly pine (*Pinus taeda* L.) seedlings were planted there in early spring 1992. Experimental treatments included three levels of organic matter removal: stem-only; whole tree; and whole tree plus all forest floor, in combination with three levels of compaction: none; moderate; and severe. Plots were split for competition control treatments. Previous analyses, using all live trees in the measurements plots, indicated that competition control was the sole significant treatment effect on tree height for the first 14 years of this study. In this analysis we used height growth for the 10 trees in each plot identified as dominant or co-dominant. Both organic matter removal and soil compaction treatments have had a significant effect on height growth of dominant and co-dominant trees, suggesting that site preparation may affect merchantable timber production.

INTRODUCTION

Forests are subject to large-scale disturbance by harvesting and site preparation. An important question raised by forest soil scientists is whether soils can sustain the long-term needs of forest stands under the conditions of intensive site preparation, shortened rotations, and higher utilization standards (Powers and others 1990). Evaluating the fundamental relationships between soil type, drainage class, long-term productivity, and forest management practices, is integral to deepening our understanding of the lasting effects of modern silvicultural techniques. The effects that harvest intensity and site preparation have on soil properties and stand productivity, for a variety of forested ecosystems, are being analyzed as part of the U.S. Forest Service Long Term Soil Productivity (LTSP) network (Fleming and others 2006, Powers and others 2005, Sanchez and others 2006).

Previous analyses of the NC LTSP installations indicated a significant positive effect of competition control on height growth, but no effect of organic matter removal or soil compaction (Powers and others 2005, Sanchez and others 2006). However, these analyses included all live trees in the measurement plots and do not provide any information on the merchantable wood on the plots. Site index curves reflect expected tree height growth during a rotation, and are commonly used to compare productivity of specific tree species at different locations or on different soil types. Site index curves usually are generated based on heights of dominant and co-dominant trees on the site. By including only dominant and co-dominant trees in this analysis, we were able to gain an operational view of treatment effects. Additionally, comparisons of stem size distributions between treatment plots allowed us to examine treatment impacts on site productivity, as shifts in stem size distribution can indicate changes in merchantability of woody biomass (Hennessey and others 2004).

METHODS

An LTSP installation followed the clearcutting of a 60-year-old natural pine-hardwood stand on the Lower Coastal Plain, near New Bern, NC (34°53'58"N, 76°48'30"W) in 1991. Nine treatment plots (0.4-ha each) were established and assigned a 3 by 3 factorial combination of organic matter removal [stem-only (OM_0), whole-tree (OM_1), and whole-tree plus forest floor (OM_2)] and soil compaction [none (C_0), medium (C_1), and severe (C_2)] treatments (Eaton and others 2004). The treatment combinations were randomly assigned on each of three blocks. Treatment plots were then split to include total-competition control and no-competition control treatments. One block was located on a Goldsboro series soil (fine loamy, siliceous, thermic aquic Paleudults) and two blocks were located on a Lynchburg series soil (fine loamy, siliceous, thermic aeric Paleaquults). Site index at 50 years was 27.4 m for the Goldsboro block, and 26.2 m for the Lynchburg blocks (Goodwin 1989). Each split plot contained one 0.07 ha measurement plot where 80 loblolly pine trees were planted at a 3 by 3 m spacing.

To prepare the site, all trees were directionally felled into their respective plots. The OM_0 treatment was implemented by de-limbing trees in the plot and removing the bole, either by skidder in the C_1 and C_2 treatment plots, or by crane positioned adjacent to the plot in the C_0 plots. The OM_1 treatment was implemented in the same way except the entire tree was removed from the plot. The OM_2 treatment included the same procedures as the OM_1 treatment and the additional removal of the entire forest floor, either by bulldozer or hand-raked, depending on the compaction level. No machinery was allowed on the C_0 treatment plots, while the C_1 plots were compacted using a smooth drum vibratory roller passing once over the entire plot with no vibration. Compaction on the C_2 treatment was accomplished by passing the drum roller, on full vibration, twice over the entire

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plot. Vegetation control was carried out using brush saws and herbicide, as needed, to remove all non-planted vegetation.

Height measurements of all trees in the measurement plots were recorded annually for the first 10 years of the study. Heights were measured using height poles or a hypsometer. On each plot, ten trees, consistently identified as dominant or co-dominant, were re-measured at year 14. Analysis of variance (SAS 2003) was used to test for treatment effects on tree height.

RESULTS

Statistical analyses, using only the 10 dominant/co-dominant tree height values, indicate significant ($p \leq 0.05$) organic matter removal, soil compaction, and competition control effects at multiple ages during stand development (table 1). Organic matter removal treatments significantly ($p \leq 0.05$) impacted tree height for the first 5 years after planting (table 2). Mean tree heights in the OM_1 treatment were greater in all years. Tree heights on the C_0 plots were greater than on compacted plots (C_1 and C_2) from ages one through age three, but mean heights in the C_2 treatments were consistently higher after age four (table 2). Tree heights in the total competition control treatment plots were always higher than in the no competition control plots (table 2). Previous analyses, utilizing all live trees, indicated no significant main treatment effects but a significant competition control effect on tree height in nearly every year (Powers and others 1990, Sanchez and others 2006).

Histograms were produced to depict the stem volume frequency distribution by soil compaction treatment (fig. 1). Stem volume distribution showed two peaks for each soil compaction treatment and illustrate the strong competition control effect. Shifts in the mean within the two competition peaks for each of the three soil compaction levels confirm the stronger effect of competition control than soil compaction. There was a shift in the mode value, toward increasing volume, with increasing soil compaction in the competition controlled plots. Additionally, there were different distribution patterns by treatment, suggesting that soil compaction may impact harvest schedules by changing the number of harvests necessary to collect merchantable timber (C_2) or by changing the rotation length (C_1).

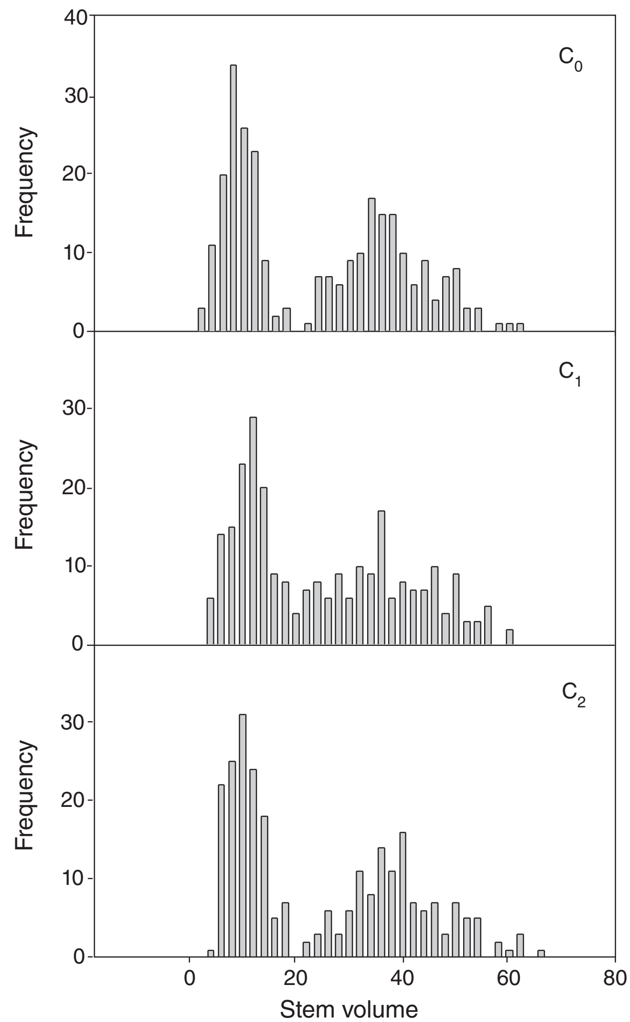

Figure 1—Histogram of loblolly pine stem volume distribution.

Table 1—Probability values (P > f) for treatment effects on the height of the 10 dominant or co-dominant loblolly pine trees per plots, at the Croatan LTSP study

Year	Organic matter removal	Soil compaction	Competition control
1	0.020	0.012	0.579
2	0.030	0.897	<0.0001
3	0.017	0.929	<0.0001
4	0.016	0.735	<0.0001
5	0.042	0.169	<0.0001
6	0.096	0.087	<0.0001
7	0.180	0.081	<0.0001
8	0.191	0.044	<0.0001
9	0.391	0.035	<0.0001
10	0.250	0.075	<0.0001
14	0.355	0.182	<0.0001

DISCUSSION

Previous analyses focused on detecting differences in mean heights for all surviving trees and found that only the competition control treatment was significant. Alternatively, when examining only the dominant and co-dominant trees, indices of merchantable timber, significant treatment effects were also detected for the organic matter removal and compaction treatments. The significant effect that organic matter removal had on height in years 1 through 6 and the consistently greater heights in the OM_1 treatment are likely

Table 2—Loblolly pine mean height (m) using the 10 dominant and co-dominant trees per measurement plot, at the Croatan LTSP study. Means were generated for individual main effect and split-plot treatments. Numbers in parentheses represent the treatment levels; letters represent results for Tukey's means separation test. Within a column, for a given year, means with the different letters are significantly different at α ≤ 0.05 level.

Year	Organic matter removal	Compaction	Competition control
1	(0) 0.55ab	(0) 0.56	(0) 0.55
	(1) 0.57a	(1) 0.55	(1) 0.56
	(2) 0.52b	(2) 0.55	
2	(0) 1.39ab	(0) 1.40	(0) 1.24a
	(1) 1.49a	(1) 1.37	(1) 1.53b
	(2) 1.28b	(2) 1.39	
3	(0) 2.59ab	(0) 2.61	(0) 2.24a
	(1) 2.74a	(1) 2.58	(1) 2.96b
	(2) 2.46b	(2) 2.60	
4	(0) 4.09ab	(0) 4.08	(0) 3.50a
	(1) 4.28a	(1) 4.11	(1) 4.73b
	(2) 3.97b	(2) 4.15	
5	(0) 5.34ab	(0) 5.27	(0) 4.55a
	(1) 5.59a	(1) 5.41	(1) 6.24b
	(2) 5.27b	(2) 5.51	
6	(0) 6.46	(0) 6.40	(0) 5.55a
	(1) 6.74	(1) 6.58	(1) 7.58b
	(2) 6.49	(2) 6.71	
7	(0) 7.84	(0) 7.76	(0) 6.70a
	(1) 8.11	(1) 8.00	(1) 9.20b
	(2) 7.90	(2) 8.10	
8	(0) 9.00	(0) 8.89a	(0) 7.73a
	(1) 9.31	(1) 9.17ab	(1) 10.53b
	(2) 9.09	(2) 9.34b	
9	(0) 10.08	(0) 9.85a	(0) 8.66a
	(1) 10.31	(1) 10.23ab	(1) 11.65b
	(2) 10.07	(2) 10.38b	
10	(0) 11.36	(0) 11.21	(0) 9.83a
	(1) 11.74	(1) 11.51	(1) 13.18b
	(2) 11.41	(2) 11.79	
14	(0) 15.53	(0) 15.35	(0) 13.77a
	(1) 15.81	(1) 15.47	(1) 17.38b
	(2) 15.38	(2) 15.90	

a result of several factors. The bole-only removal treatment (OM_0) left the most biomass on-site, but also allowed the highest amount of competition due to the low site disturbance. Additionally, the OM_0 plots had generally cooler summertime soil temperatures (Eaton and others 2004) which may decrease growth due to reduced mineralization rates (Powers 1990). Higher amounts of biomass, in the form of branches, provided a higher quantity of nutrients, but those may not be readily accessible. Conversely, on the most severe organic matter removal treatments (OM_2), reduced nutrient levels due to the removal of the forest floor may have reduced height growth, especially in the first 6 years (Sanchez and others 2006).

CONCLUSION

Previous analysis of LTSP data focused on the yearly height measurements of all living trees in the measurement plot to determine if there were significant differences due to treatments. Other than the drastic differences due to competition control, no treatment effects were found. Comparison of trees that would normally be measured for site index curves (dominant and co-dominant) indicate that both the compaction and organic matter treatments have had a significant effect on the height growth; a trend that continued through year 14, and could have important operational impacts. Additional data collection and further study is recommended to resolve the differences between the two methods of analysis. Because site index generally is used as a field tool to evaluate productivity, these differing results indicate that the target audience should be considered when future analysis and reporting is done.

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PONDERING THE MONOTERPENE COMPOSITION OF *PINUS SEROTINA* MICHX.:CAN LIMONENE BE USED AS A CHEMOTAXONOMIC MARKER FOR THE IDENTIFICATION OF OLD TURPENTINE STUMPS?

Thomas L. Eberhardt, Jolie M. Mahfouz, and Philip M. Sheridan[1]

Abstract—Wood samples from old turpentine stumps in Virginia were analyzed by GC-MS to determine if the monoterpene compositions could be used for species identification. Given that limonene is reported to be the predominant monoterpene for pond pine (*Pinus serotina* Michx.), low relative proportions of limonene in these samples appeared to suggest that these stumps were not from pond pine. Unexpectedly, analysis of wood samples from live trees identified as pond pine did not consistently confirm a high relative proportion of limonene. Further sampling of half-sib pond pine trees suggested that limonene may be an unreliable chemotaxonomic marker for pond pine hybrids.

INTRODUCTION

Longleaf pine (*Pinus palustris* Mill.) has a well established history in naval stores production from early turpentining operations to the subsequent processing of old resinous stumps (Gardner 1989). We were interested in comparing turpentine stumps from central and southeastern Virginia to determine their taxonomic identity and so establish the true range and specific sites that longleaf pine occupied in Virginia. Data reported for the fresh oleoresin from most southern pines (e.g., *P. palustris, P. taeda, P. echinata, P. elliottii*) have shown that α-pinene constitutes 50-80 percent of the monoterpenes detected (Hodges and others 1979, Strom and others 2002). The second most abundant monoterpene, β-pinene, accounts for 20-40 percent of the monoterpenes detected. Pond pine is the exception with limonene accounting for as much as 90 percent of the detected monoterpenes (Mirov 1961). We hypothesized that comparisons of the monoterpene compositions from the stump wood samples with wood samples from known sources, along with data from the literature, may allow the identification of said stump wood samples. Given the unique monoterpene composition reported for pond pine, we also speculated that high levels of limonene (>90 percent) could be used to positively identify stump samples as pond pine.

MATERIALS AND METHODS

Highly weathered wood samples were collected from old turpentine stumps located in Caroline, Prince George, Southampton, and Sussex counties in Virginia. An electric drill was used to collect shavings from the interior of wood samples with minimal heat generation. A drill was also used to sample longleaf pine stumps in an experimental forest in the Calcasieu Ranger District of the Kisatchie National Forest in Louisiana. A razor blade was used to cut heartwood and sapwood shavings from a pond pine branch that had been collected in southeastern Virginia. Wood cores from live pond pine trees were collected near Saucier, MS. Shavings were cut from these cores with a razor blade.

For the GC-MS analyses, wood shavings (1 g) were steeped in methylene chloride (5 ml). The resultant extracts were analyzed on a Hewlett Packard 6890 gas chromatograph equipped with a Hewlett Packard 5973 mass selective detector and an HP-INNOWax column (0.25 mm ID × 60 m length × 25 µm film thickness). The column was programmed to hold for 1 min at 40 °C, increase to 80 °C at a rate of 16 °C/ min, and then to 240 °C at a rate of 7 °C/ min, with the final temperature being held for 10 minutes. The temperatures for the injector inlet and mass detector were maintained at 200 °C and 225 °C, respectively. Peaks were identified by spectral match with NIST 98 (NIST, Gaithersburg, MD) and in-house chemical libraries.

RESULTS AND DISCUSSION

Monoterpenes Present in Stump Wood Samples

GC-MS analysis of the stump wood samples showed that α-pinene was the most abundant monoterpene in 4 out of 6 cases (table 1). The second most abundant compound was the oxidized monoterpene, α-terpineol. This latter result was not surprising since wood naval stores (i.e., those from old pine stumps) have been reported to contain high amounts (50-60 percent) of α-terpineol (Buchanan 1963). Other oxidized monoterpenes (e.g., camphor, fenchyl alcohol, and borneol) were also present in significant amounts. Similarities in the monoterpene compositions for most southern pines prevented us from demonstrating that the stumps were specifically from longleaf pine; however, the absence of high relative proportions of limonene suggested that the turpentine stumps were not from pond pine. Samples of pond pine were thus sought to confirm the predominance of limonene among the monoterpenes present in the wood for this species.

Effect of Sample Handling on Limonene Levels

Heartwood and sapwood shavings from a pond pine branch were analyzed, and this confirmed that limonene made up a high proportion of the monoterpenes detected by GC-MS. Shavings of sapwood were also kept in open containers for various periods of time to determine whether low limonene levels could have resulted from sample handling. Results showed that the exposure periods did not seem to alter the relative amounts of limonene (table 2); the relative amounts

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Table 1—Percentage compositions of monoterpenes and methyl chavicol in stump wood samples from selected counties in Virginia

Monoterpenes	Stump Wood Samples					
	Caroline (Scholl)[a]	Caroline (Pines)	Prince George	Southampton[b]	Sussex (John Hancock)	Sussex (Joseph Pines)
	percent					
α-Pinene	47.37	48.59	18.06	58.22	12.07	45.30
α-Fenchene	0.80	0.42	3.14	0.58	5.60	0.74
Camsphene	3.59	0.24	5.46	3.10	7.58	2.99
β-Pinene	1.55	2.41	-	1.25	-	2.75
Myrcene	1.29	1.88	-	0.03	-	0.19
α-Phellandrene	-	3.23	0.41	-	-	-
α-Terpinene	-	1.27	1.33	-	-	-
Limonene	10.96	8.80	1.63	9.29	0.42	4.61
β-Phellandrene	-	6.58	-	-	-	0.31
p-Cymene	0.74	0.11	47.97	0.28	19.14	1.40
Terpinolene	1.26	2.23	1.89	1.67		1.11
Fenchone	0.36	-	2.88	0.26	13.89	2.32
Camphor	1.10	-	6.58	0.82	19.95	4.36
Fenchyl Alcohol	2.83	2.78	1.69	1.92	0.15	0.89
Terpinen-4-ol	1.62		1.97	0.93	11.22	3.64
Methyl Chavicol	0.20	0.63	-	2.55	0.52	6.89
α-Terpineol	23.54	17.04	4.72	16.18	7.27	21.58
Borneol	2.78	3.26	2.27	2.91	2.18	0.92

[a]putative loblolly pine; specific site indicated in parentheses.
[b]putative longleaf pine.
Source: Eberhardt and others (2007).

of limonene in sapwood and heartwood samples were generally similar.

Assessment of Limonene Predominance in Pond Pine

Analysis of pond pine samples from a variety of sources failed to consistently demonstrate that limonene was the predominant monoterpene among those detected by GC-MS. Given the possibility of inaccurate species identification during sample collection, additional samples were obtained from three 30 year old half-sib pond pine trees near Saucier, MS. Since α-pinene was found to be the predominant monoterpene in one of these trees, it was speculated that a hybrid had been sampled. Eighteen additional cores were collected and it was found that α-pinene was predominant in 4 of the 16 trees with detectable monoterpene levels (fig. 1). Three of the cores were from grafted trees (15, 16, and 17). It is of particular interest to determine whether cores 2, 5, and 10 (half-sibs from seed) are indeed hybrids of pond pine. Although pond pine does hybridize with loblolly pine (*Pinus taeda* L.), this does not often occur in the natural range because of differences in flowering dates (Bramlett 1990). We attribute the discrepancies in monoterpene composition of the pond pine trees we sampled to hybridization. These trees, raised from seed from open-pollinated pond pine parents, were likely contaminated with loblolly pine pollen in the seed orchard.

Aging of Longleaf Pine Stumps under Field Conditions

In an effort to determine the changes to the monoterpene compositions in stumps under field conditions, samples of heartwood and sapwood from longleaf pine stumps were collected 1 week, 1 month, 6 months, and 1 year after harvesting. Relative monoterpene composition of the heartwood and of the sapwood did not appear to change over the initial 6-month period; samples collected 1 year after harvesting are still being analyzed. Average values for the heartwood and sapwood monoterpenes were calculated and are shown in table 3. Both the total yield of

Table 2—Selected monoterpenes in pond pine samples allowed to stand under ambient conditions

Sample type	Exposure Period	α-Pinene	β-Phellandrene	Limonene
	days	*percent*	*percent*	*percent*
Sapwood	0	0.3	0.3	97.3
	1	4.8	4.8	91.4
	2	5.9	5.9	90.5
	4	3.1	3.1	94.2
Heartwood	0	1.7	1.7	94.4

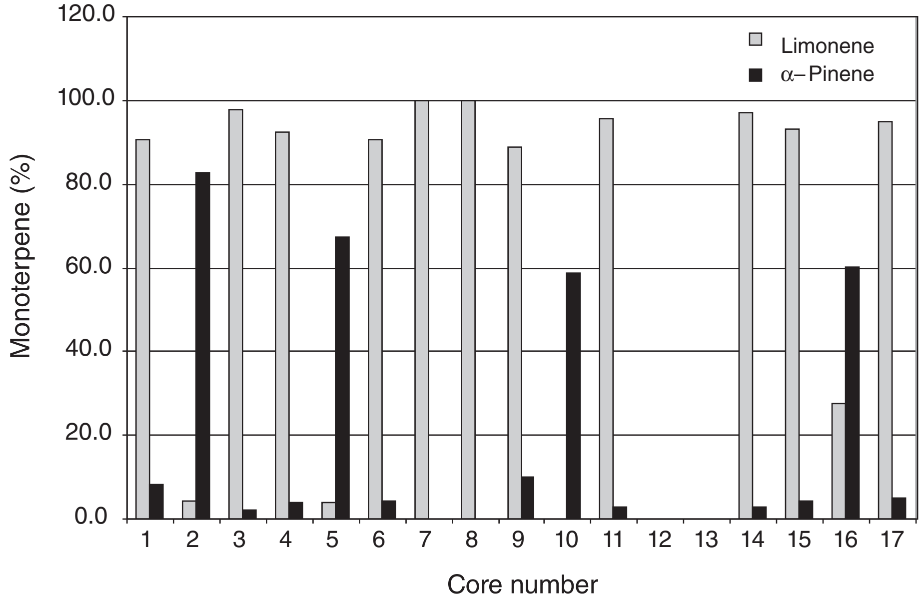

Figure 1—Limonene and α-pinene as percentages of the monoterpenes detected in cores from pond pine trees grown near Saucier, MS.

Table 3—Selected monoterpene compositions for longleaf pine stumps under field conditions

	α-Pinene	β-Pinene	α-Terpineol	Total Yield
	percent	*percent*	*percent*	*mg/g*
Sapwood	75.8 9.4	14.5 6.0	0.7 1.4	7.0 5.3
Heartwood	64.1 8.6	10.3 6.1	9.9 8.8	20.2 13.6

monoterpenes and the proportion of oxidized monoterpenes (e.g., α-terpineol) were higher in the heartwood (table 3). The former is indicative of the higher extractives contents typical of heartwood. The latter (high α-terpineol) suggests that the higher proportion of oxidized monoterpenes is not simply a function of post-harvest stump ageing. The presence of oxidized monoterpenes in pond pine stump heartwood remains to be determined.

CONCLUSIONS

Limonene is an unreliable chemotaxonomic marker for pond pines grown in environments conducive to hybridization. Since pond pine does not readily hybridize in its native range, it is unlikely that the old stump wood samples collected in Virginia were from pond pine.

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EVALUATING GROWTH ASSUMPTIONS USING DIAMETER OR RADIAL INCREMENTS IN NATURAL EVEN-AGED LONGLEAF PINE

John C. Gilbert, Ralph S. Meldahl, Jyoti N.Rayamajhi, and John S. Kush[1]

Abstract—When using increment cores to predict future growth, one often assumes future growth is identical to past growth for individual trees. Once this assumption is accepted, a decision has to be made between which growth estimate should be used, constant diameter growth or constant basal area growth. Often, the assumption of constant diameter growth is used due to the ease of calculations. To determine which assumption is appropriate for natural even-aged stands of longleaf pine, permanent plot data from the U.S. Forest Service Regional Longleaf Pine Growth Study (RLGS) can be analyzed. Data from the RLGS cover a range of age classes, basal area classes, and site indices across the Gulf States. Plots have been measured every 5 years since the establishment of the study in 1964. Results show constant basal area growth to be the more valid assumption for natural even-aged longleaf pine.

INTRODUCTION

When using increment cores (past radial growth) to predict future growth, one often assumes future growth is identical to past growth for individual trees (i.e., growth is constant over a given time period). Once this assumption is accepted, a decision has to be made between which growth estimate should be used, constant diameter growth or constant basal area growth. Often the assumption of constant diameter growth is used due to the ease of calculations. However, this may not always be the most valid approach. Clutter and others (1983) stated their southern pine data does not follow the assumption of constant diameter growth, but the assumption of constant basal area growth has not been proven invalid. To determine which assumption is appropriate for natural even-aged stands of longleaf pine, permanent plot data from the U.S. Forest Service Regional Longleaf Pine Growth Study (RLGS) were analyzed. Data from the RLGS cover a range of age classes, basal area classes, and site indices across the Gulf States. Plots have been measured every 5 years since the establishment of the study in 1964.

DATASET DESCRIPTION

In 1964, Dr. Robert M. Farrar, Jr., with the USDA Forest Service established the Regional Longleaf Pine Growth Study (RLGS) in the Gulf States (Farrar 1978). The original objective of the study was to obtain a database for the development of growth and yield predictions for naturally regenerated, even-aged longleaf pine stands. Plots were installed to cover a range of ages, densities, and site qualities. The study accounts for change in growth over time by adding a new set of plots in the youngest age class every 10 years. The study currently consists of 292 1/5-acre and 13 1/10-acre permanent measurement plots located in central and southern AL, southern MS, southwest GA, northern FL, and the sandhills of NC. At the time of establishment, plots are assigned a target basal area class of 30, 60, 90, 120, or 150 square feet per acre. They are left unthinned to grow into that class if they are initially below the target basal area. Plot selection was based upon a rectangular distribution of cells formed by: 5 age classes from 20 to 100 years, 4 site quality classes ranging from 50 to 80 feet at 50 years, 5 density classes ranging from 30 to 150 square feet per acre, and plots left unthinned to examine the dynamics of dense stands. In subsequent re-measurements, a plot is thinned back to the previously assigned target if the plot basal area has grown 7.5 square feet per acre beyond the target basal area. The thinnings are generally of low intensity and are done from below. Net measurement plots are surrounded by a similar and like-treated half-chain wide isolation strip. Plots are inventoried and treated as needed, every 5 years (Kush and others 1987, 1998).

METHODS

The RLGS dataset was divided into measurement series of ten years, which provided sets of past, current, and future observed diameters for each plot and tree. Predicted future diameters were calculated using both assumptions (See eq. 1, 2, and 3). To evaluate which assumption provided the best estimate of growth, model validation was performed for the predictions for both methods over the classes of basal area, site index, and age. The validation process used bias and accuracy criteria from Burk (1986). Equations 4 and 5 are for bias and accuracy, respectively. The models were also compared using percent mean difference (Buford 1991). Equation 6 is for percent mean difference.

Assumed Future Diameter Estimates

Constant diameter growth

(1) Future Diameter = Current Diameter + (Current Diameter – Past Diameter)

Constant basal area (BA) growth

(2) Future BA = Current BA + (Current BA – Past BA)

(3) Future Diameter = $\sqrt{\frac{FutureBA}{0.005454}}$

Validation Equations

(4) Bias = $\frac{\sum(predicted - observed)}{n}$

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(5) Accuracy = $\frac{\sum |predicted - observed|}{n}$

(Snee 1977, Burk 1986)

(6) Percent Mean Difference =

$$\left[\frac{1}{n}\sum\left(\frac{observed - predicted}{observed}\right)\right]\times 100$$

(Buford 1991)

RESULTS AND DISCUSSION

Models were evaluated using the bias and accuracy criteria from Burk (1986). Tables 1 through 3 show constant diameter and constant basal area growth bias and accuracy values for the ranges of basal areas, site indices, and ages, respectively. Figures 1 through 3 are graphical versions of constant diameter and constant basal area growth bias values for the ranges of basal areas, site indices, and ages, respectively. The constant basal area growth estimates performed significantly better at low basal areas and young ages than constant diameter growth estimates for natural even-aged stands of longleaf pine. Looking at bias and accuracy across all classes in table 4 also shows that growth estimates using the assumption of constant basal area growth were better than the estimates using the assumption of constant diameter growth.

Models were also compared using percent mean difference (Buford 1991). These results were similar to those using Burk's criteria. Table 5 shows constant diameter and basal area growth percent mean difference by ranges of basal areas, site indices, and ages. Figure 4 is a graphical version of the percent mean difference for both models across basal area classes. Again, the constant basal area growth estimates performed significantly better at low basal areas and young ages than constant diameter growth estimates.

Table 1—Constant diameter and basal area growth bias and accuracy by basal area classes for trees from the RLGS dataset

Basal Area (*square feet/acre*)	N	CD_Bias	CD_Accuracy	CBA_Bias	CBA_Accuracy
30	3635	0.13	0.25	-0.03	0.22
60	9656	0.15	0.24	0.03	0.18
90	18344	0.12	0.19	0.06	0.16
120	22562	0.12	0.18	0.07	0.16
150	10506	0.13	0.20	0.09	0.17

CD_ prefix = Constant Diameter Growth; CBA_ prefix = Constant Basal Area Growth.

Table 2—Constant diameter and basal area growth bias and accuracy by site indices for trees from the RLGS dataset

Site Index (*feet*)	N	CD_Bias	CD_Accuracy	CBA_Bias	CBA_Accuracy
50	10306	0.05	0.15	0.02	0.14
60	13324	0.12	0.20	0.04	0.17
70	24624	0.18	0.23	0.09	0.18
80	16449	0.10	0.19	0.05	0.16

CD_ prefix = Constant Diameter Growth; CBA_ prefix = Constant Basal Area Growth.

Table 3—Constant diameter and basal area growth bias and accuracy by age classes for trees from the RLGS dataset

Age (*years*)	N	CD_Bias	CD_Accuracy	CBA_Bias	CBA_Accuracy
20	28623	0.21	0.26	0.10	0.19
40	20177	0.09	0.16	0.05	0.15
60	9572	0.03	0.15	0.01	0.14
80	4975	0.02	0.15	0.00	0.15
100	1356	0.00	0.16	-0.01	0.16

CD_ prefix = Constant Diameter Growth; CBA_ prefix = Constant Basal Area Growth.

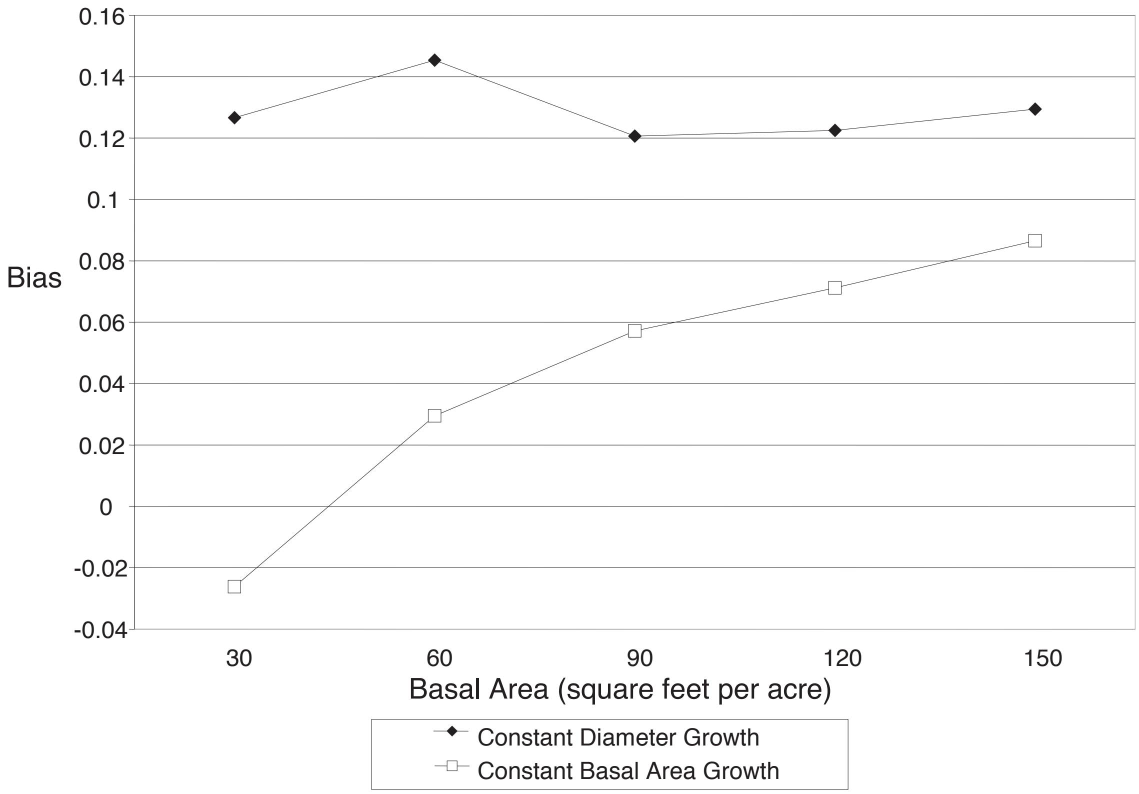

Figure 1—Constant diameter and basal area growth bias by basal area classes for trees from the RLGS dataset.

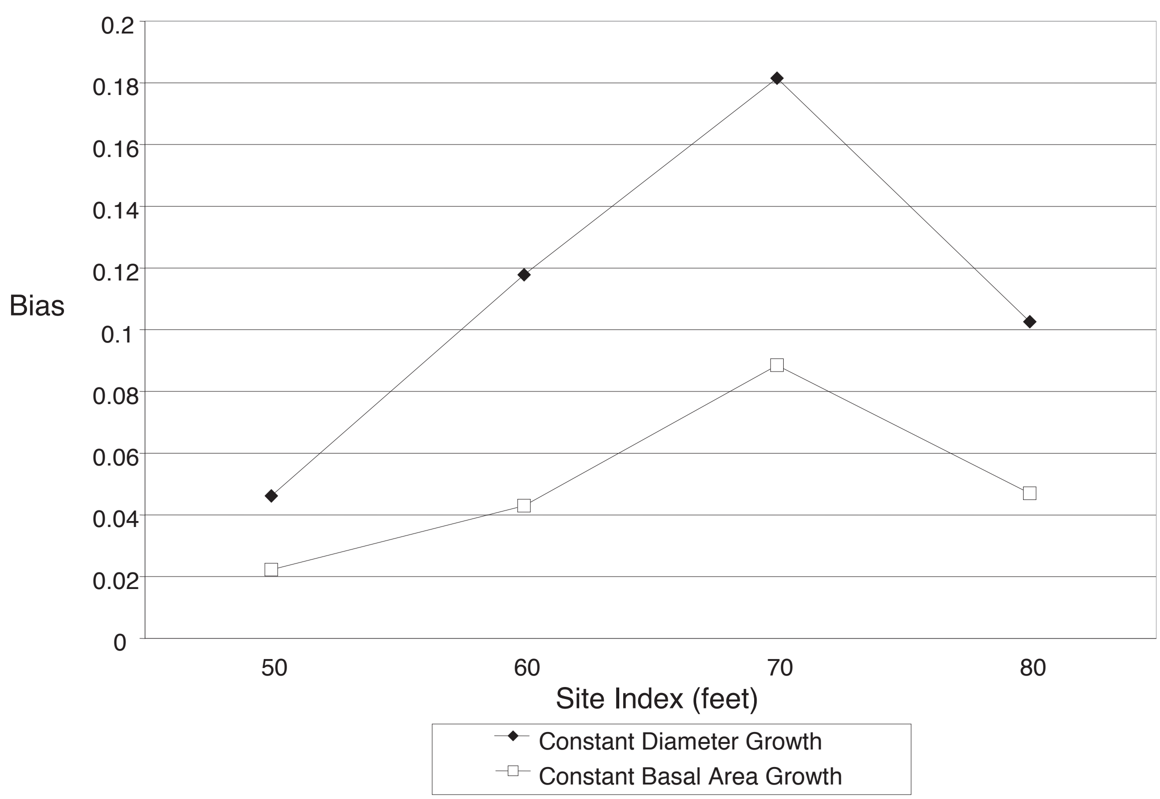

Figure 2—Constant diameter and basal area growth bias by site indices for trees from the RLGS dataset.

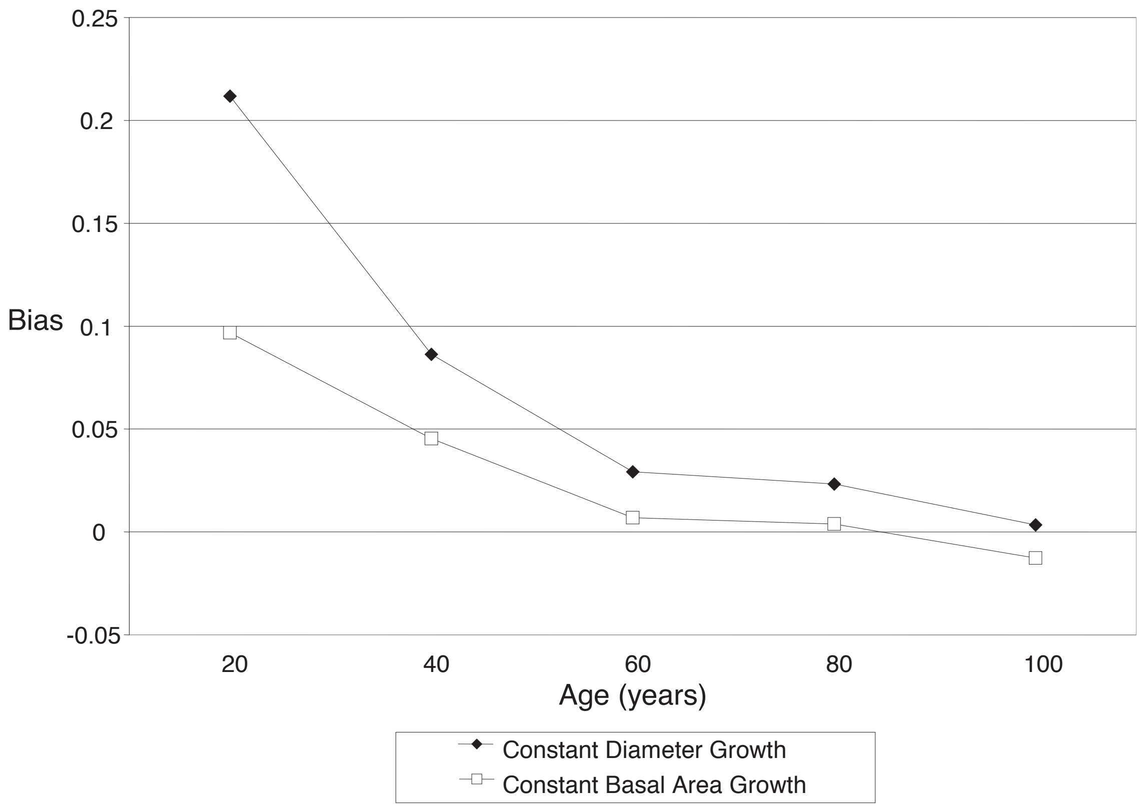

Figure 3—Constant diameter and basal area growth bias by age classes for trees from the RLGS dataset.

Table 4—Constant diameter and basal area growth bias and accuracy over all classes for trees from the RLGS dataset

N	CD_Bias	CD_Accuracy	CBA_Bias	CBA_Accuracy
64703	0.13	0.20	0.06	0.17

CD_ prefix = Constant Diameter Growth; CBA_ prefix = Constant Basal Area Growth.

Table 5—Constant diameter and basal area growth percent mean difference by ranges of basal areas, site indices, and ages for trees from the RLGS dataset

Classification	Ranges	CD_Mean Difference (%)	CBA_Mean Difference (%)
Basal Area (square feet per acre)	30	0.61	0.31
	60	0.66	0.32
	90	0.41	0.25
	120	0.45	0.31
	150	0.49	0.35
Site Index (feet)	50	0.25	0.21
	60	0.64	0.35
	70	0.71	0.43
	80	0.18	0.13
Age (years)	20	0.97	0.57
	40	0.15	0.13
	60	0.06	0.06
	80	0.03	0.03
	100	0.02	0.02

CD_ prefix = Constant Diameter Growth; CBA_ prefix = Constant Basal Area Growth.

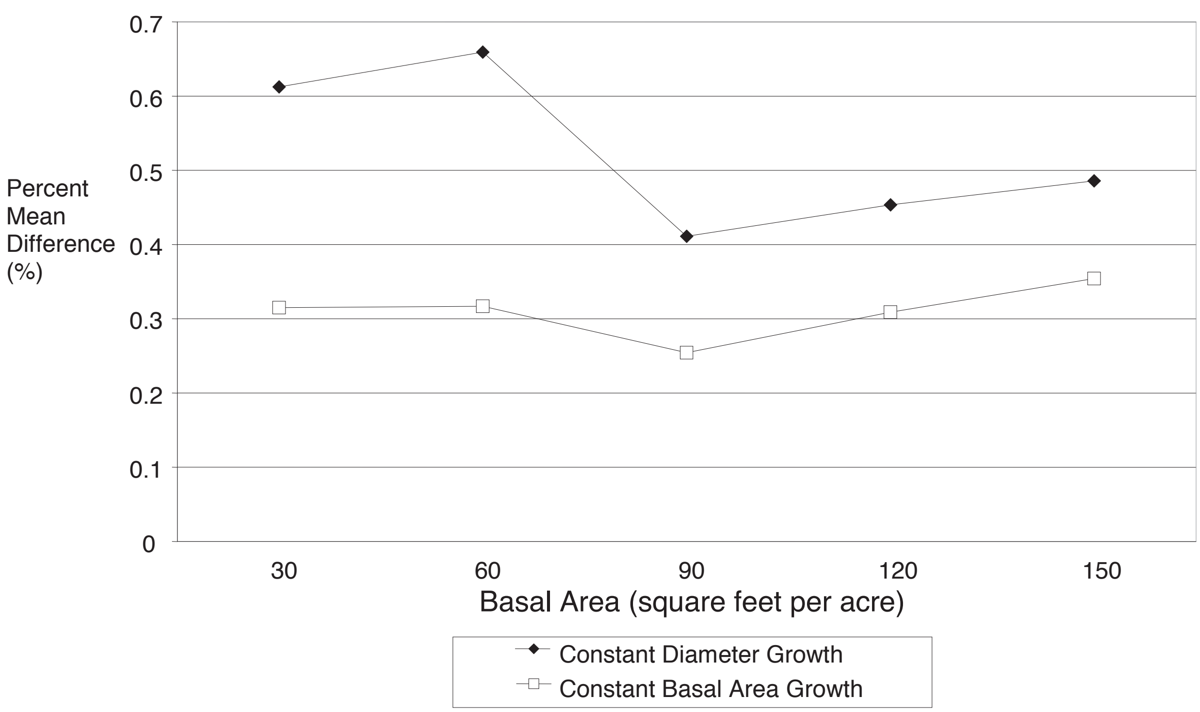

Figure 4—Constant diameter and basal area growth percent mean difference by basal area classes for trees from the RLGS dataset.

CONCLUSIONS

For natural even-aged stands of longleaf pine, growth estimates using the assumption of constant basal area growth were consistently better than the estimates using the assumption of constant diameter growth in all measurements of validation. However, the magnitude varies across the ranges of basal areas, site indices, and ages. It is up to the user to concentrate on the ranges of interest. The final choice between the two methods is greatly dependent on acceptable error, ease of calculations, and time.

ACKNOWLEDGMENTS

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EFFECTS OF PRESCRIBED BURNING, MECHANICAL, AND CHEMICAL TREATMENTS TO CURTAIL RHODODENDRON DOMINANCE AND REDUCE WILDFIRE FUEL LOADS

Chuck Harrell and Shep Zedaker[1]

More than a century of fire suppression has resulted in the increased abundance of Rosebay Rhododendron (*Rhododendron maximum* L.) throughout the Appalachian Mountains. Rhododendron has historically been most frequently associated with mesic sites, but can now be found proliferating toward drier midslope and ridgetop areas. The increased presence of rhododendron in understories of the Appalachian Mountains has negatively affected forest health. Two such negative effects are the stunted growth or absence or overstory tree regeneration and the creation of dangerous fuel complexes. The purpose of this study was to determine the efficacy and efficiency of various vegetation control measures (and their combinations) on the vigor of rhododendron and fuel loading within rhododendron thickets. The three vegetation control procedures were prescribed fire, herbicide application, and mechanical cutting.

Our experimental design consisted of three replications of an unbalanced split-plot design. Each replication contained eight half-acre study plots, each plot representing one of the following treatments:

1. Prescribed fire
2. Prescribed fire and herbicide
3. Mechanical cutting and prescribed fire
4. Herbicide and prescribed fire
5. Mechanical cutting
6. Mechanical cutting and herbicide
7. Herbicide
8. Control (no treatment)

Prescribed fires were ignited by hand and by helicopter, with target fire behavior of high-intensity 4-6 foot (1.22-1.83 m) flame lengths. Chainsaw crews performed the mechanical cutting treatment, felling all *R. maximum* stems on a plot. Backpack sprayers were used to implement herbicide application. Imazapyr as Stalker® and Triclopyr as Garlon 4® were applied either as a basal spray with a Hy-Grade EC® vegetable oil carrier or as a foliar spray with a water carrier.

Fuel loading by fuel class and live rhododendron stems per acre in 2-cm stem classes are the data discussed in this summary. Mechanical cutting significantly increased fine woody fuel loading within an *R. maximum* thicket. Herbicide application and prescribed burning showed no significance in fine woody fuel addition/reduction. Prescribed burning significantly reduced litter fuel loading on sites dominated by *R. maximum*. In the first year after treatment, none of our prescriptions reduced total fuel loading**.**

Mechanical cutting and prescribed burning treatments resulted in heavy basal sprouting. Herbicide application successfully controlled sprouting as a combination treatment but was unable to control larger *R. maximum* stems. Some replications of our prescribed burning treatments resulted in excellent topkill of *R. maximum*, while others were mostly ineffective in achieving any mortality.

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SEGMENTED POLYNOMIAL TAPER EQUATION INCORPORATING YEARS SINCE THINNING FOR LOBLOLLY PINE PLANTATIONS

A. Gordon Holley, Thomas B. Lynch, Charles T. Stiff, William Stansfield[1]

Abstract—Data from 108 trees felled from 16 loblolly pine stands owned by Temple-Inland Forest Products Corp. were used to determine effects of years since thinning (YST) on stem taper using the Max–Burkhart type segmented polynomial taper model. Sample tree YST ranged from two to nine years prior to destructive sampling. In an effort to equalize sample sizes, tree data were classified into three groups: 2 and 3, 4 and 5, and 6 to 9 years since thinning. A modified Max-Burkhart segmented taper model was fitted to each of the three YST categories in order to detect any trends in the coefficients. Multiple coefficients were then expressed as functions of YST. The resulting three-segment equation included the independent variable of YST. The resulting taper equation predicts expected changes in shape of loblolly pine trees following thinning activities.

INTRODUCTION

Volume equations are useful predictors of total stem volume or merchantable volume within given merchantability constraints. However, taper equations can provide estimates of diameter at any point along a stem. Such equations can be integrated through calculus to derive volume estimates, permitting differing merchantability limits to be specified for a broad and changing array of forest products. Heger (1965) found trees with less taper can yield more volume than like trees having more taper. Several stand related silvicultural processes can alter the rate of taper for individual trees. One of the most important forest management practices is forest thinning. Although thinning has been shown to substantially modify diameter growth, it will generally have negligible effects on height growth for most species (Davis and others 2001).

On the other hand it is possible that thinning may affect tree shape in a way that cannot be completely explained by corresponding changes in the d.b.h.-height ratio. This study seeks to model and quantify the changes in tree taper as the time since thinning operations increase.

TAPER MODELS

Numerous models to explain taper have been developed: Kozak and others (1969), Ormerod (1973), Thomas and Parresol (1991), and Valentine and Gregoire (2001). A segmented polynomial model (SPM) approach was presented by Max and Burkhart (1976). The SPM is able to describe the general shape of a tree by separating the stem into two or more sections. Max and Burkhart's SPM (eq. 1) used three segments to describe the shape of a tree. The bottom bole section, which includes the butt, is modeled as a frustum of a neiloidal solid, the middle of the bole is assumed to take the shape of a frustum of a paraboloidal solid, and the top portion is assumed to be conoid. In this system, three additive models are grafted together by way of incorporating join points between the three segments. A smooth functional form across the join points is obtained by conditioning to ensure continuity and equality of first partial derivatives across the join points. Upper-stem diameters can be estimated anywhere on the bole by using an additive series of mathematical models that enter or exit the model depending on a sequence of indicator variables.

$$\frac{d^2}{D^2} = b_1(x-1) + b_2(x^2-1) + b_3(a_1-x)^2 I_1 + b_4(a_2-x)^2 I_2 \qquad (1)$$

where x is h/H, h is height to upper-stem diameter d, H is total tree height, d is diameter at upper-stem height h, D is d.b.h., and indicator variables are: $I_1 = 1$ if $x < a_1$, otherwise $I_1 = 0$ and $I_2 = 1$ if $x < a_2$, otherwise $I_2 = 0$.

Since its first application to loblolly pine (P*inus taeda*) in 1976 the Max-Burkhart SPM has been used successfully in numerous situations for coniferous species. Valenti and Cao (1986) incorporated the use of crown ratio into the Max-Burkhart SPM taper model to achieve a better fit of stem taper. The a_1 and b_1 parameters in the basic Max-Burkhart SPM were replaced with logarithmic and hyperbolic functions of crown ratio, respectively. Model 2, rewritten in the following form, is:

$$d = D\sqrt{\left(c_1 + \frac{c_2}{CR}\right)z + b_2 z^2 + b_3\left(z - \left(c_3 + c_4 * \ln(CR)\right)\right)^2 I_1 + b_4(z-a_2)^2 I_2} \qquad (2)$$

where z is $(1-h/H)$, h is height to upper-stem diameter d, H is total tree height, d is diameter at upper-stem height h, D is d.b.h., CR is crown ratio, and $I_1 = 1$ if $z > c_2 + c_3 \ln CR$, otherwise $I_1 = 0$ and $I_2 = 1$ if $z > a_2$, otherwise $I_2 = 0$.

By incorporating crown ratio into the model, upper-stem diameter estimation bias was reduced by five percent and an R^2 of 96.9 percent was obtained.

Valenti and Cao's modification of the Max-Burkhart SPM may have promise for adaptation to variation in stem form due to factors such as thinning. The Max-Burkhart model might be modified by modeling the parameters as functions of years since thinning (YST).

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DATA AND ANALYSIS

Data for this study were from trees felled from Temple-Inland Forest Products Corp. loblolly pine plantations throughout eastern Texas. 108 sample trees were selected across 16 separate stands that spanned ages from 13 to 31 years and had been growing from 2 to 9 years since thinning operations. Each sample tree was prepared after felling as follows: stump height was measured; total height above stump height was measured; at 1, 2.5, and 4.5 feet above the stump, diameter and bark thickness were measured; and finally the stem was marked at five-foot intervals from the stump to the terminal bud. The stem was bucked into 5 foot bolts according to the markings. From each bolt two d.o.b. measurements (0.1 inch) were taken perpendicular to one another with a caliper.

The data were divided into three classes of YST (2 and 3, 4 and 5, and 6 to 9 years) with an approximately equal number of observations. Equation (1) was fitted separately to each class of YST using non-linear regression techniques in SAS NLIN (SAS 2004). The resulting coefficients were plotted against the class means in order to detect any trends. Coefficients that showed trends were replaced in the model using three functions in combinations in a stepwise fashion. Following Valenti and Cao (1986) functions examined in the model were: (a) linear, c_0+c_1CR, (b) hyperbola, c_0+c_1/CR, and (c) logarithm, $c_0+c_1\ln CR$.

Thus far the best combination of replacement parameters was found to be a model with parameters $a_1 = c_3+c_4*\ln(YST)$ and $b_1 = c_1+c_2/YST$. The resulting modified equation has the following form:

$$d = D\sqrt{\left(c_1-\frac{c_2}{YST}\right)(1-x)+b_2\left(1-x^2\right)+b_3\left((1-x)-\left(c_3+c_4*\ln(YST)\right)\right)^2 I_1 + b_4\left((1-x)-a_2\right)^2 I_2}$$

$$\text{Where}\quad I_1=\begin{cases}1, \text{if } (1-x)<c_3+c_4\ln(YST)\\ 0, \text{otherwise}\end{cases}\quad \text{and}\quad I_2=\begin{cases}1, \text{if } (1-x)<a_2\\ 0, \text{otherwise}\end{cases}\qquad (3)$$

with parameter estimates for equation 3 shown in table 1.

Table 1—Estimates of the parameters from equation 3

Parameters	Parameter Estimates
b_2	2.772079
b_3	-2.968376
b_4	69.259808
a_2	0.909326
c_1	0.295761
c_2	-0.418517
c_3	0.215086
c_4	0.019247

CONCLUSIONS

Modification of parameters in a Max-Burkhart SPM equation adjusted for years since thinning indicated significant differences in stem form due to years since thinning. The equation was modified by replacement of parameters by functions of years since thinning as indicated previously. To date this equation, modified to account for years since thinning, appears to have the best performance of the taper functions that have been fitted to these data. Further testing and validation is warranted using supplementary sample trees and further modifications to the model parameters. In addition, further testing should be evaluated with individual trees and appropriate groupings of trees in the data set.

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LONGLEAF PINE (*PINUS PALUTRIS*) RESTORATION ON GULF LOWER COASTAL PLAIN FLATWOODS SITES: ROLE OF SHRUB CONTROL AND PHOSPHOROUS FERTILIZATION

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Abstract—The longleaf pine (*Pinus palustris*) ecosystem is one of the most threatened ecosystems in North America. Restoration of this ecosystem on flatwoods sites is difficult because of the thick shrub layer and limited nutrient availability of phosphorus (P) that can cause longleaf pine seedlings to remain in the grass stage for a number of years. We hypothesized that elimination of the shrub layer and P fertilization would likely increase the establishment success of planted longleaf pine seedlings on flatwoods sites. In order to test the hypothesis, a trial was established at the Naval Live Oaks area of the Gulf Islands National Seashore, FL with four treatments using a randomized complete block design. The treatments included: 1) Mechanical woody stem removal (M), 2) P fertilization (P), 3) M+P, and 4) Control. First and second year survival, root collar diameter, height, and stem volume index were compared among treatments using ANOVA. After two growing seasons, seedlings in the M+P treatment had slightly greater stem volume compared to seedlings in other treatments ($P < 0.05$). However, survival was poor for all treatments and no seedlings had emerged from the grass stage in any of the treatments.

INTRODUCTION

The longleaf pine (*Pinus palustris*) ecosystem is one of the most threatened ecosystems in North America with less than three percent of the original area remaining today (Brockway and Outcalt 1998, Jose and others 2006). Historically, longleaf pine could be found on sandhill, upland hardwood, and flatwoods sites. The species has the ability to produce a high quality timber product and provides quality habitat for many wildlife species. Because of the positive economic and ecological benefits associated with this species, longleaf pine is an ideal candidate for restoration (Brockway and others 2005). Restoration of longleaf pine, however, can be a difficult process, particularly on flatwoods sites. On these sites, restoration of the overstory is often hampered by the thick shrub layer characteristic of flatwoods sites. Under intense competition from shrubs, longleaf pine seedlings could remain in the grass stage for a number of years (Ranasinghe and others 2005). As a result, woody shrub control seems to be a logical solution to ensure successful establishment of planted longleaf pine seedlings. Another potential factor that influences seedling growth on flatwoods sites is phosphorus (P) nutrition. Phosphorous is often found to be a limiting nutrient on flatwoods sites and low availability can reduce tree growth and survival (Jokela and Long 2000). Phosphorus fertilization has been shown to increase growth of other southern pines on flatwoods sites (Colbert and others 1990, Jokela and others 1989).

The objective of this study was to quantify the survival and growth of planted longleaf pine seedlings in response to shrub control and P fertilization on flatwoods sites. We hypothesized that both shrub control and P fertilization would increase survival and growth of planted longleaf pine seedlings on flatwoods sites.

MATERIALS AND METHODS

In order to test our hypothesis, a trial was established on an ecotonal flatwoods-scrub oak site at the Naval Live Oaks area of the Gulf Islands National Seashore in Pensacola, FL with four treatments and four replications using a randomized complete block design. The treatments included: 1) Mechanical woody stem removal (M), 2) P fertilization (P), 3) M+P, and 4) Control (C).

Containerized longleaf seedlings (0-1) were planted in March at 25 seedlings per plot (15 by 15 m). In early June, woody shrubs were removed from the M and M+P plots using a brush cutter and P was applied at the rate of 55 kg ha^{-1} to the P and M+P plots as triple super phosphate fertilizer (0-45-0). Stem density was assessed for the plots at the time of treatment implementation using a 1 by 1 m subplot inside each plot. Seedlings were measured one and two years after treatment implementation.

Initial stem density of woody shrubs and survival, root collar diameter (RCD), height (HT) and stem volume index [$SVI = RCD^2 * HT$] of longleaf seedlings were compared among treatments using ANOVA. When variables were significantly different in ANOVA ($P < 0.05$), means were separated using Duncan's multiple range test.

RESULTS

Woody Stem Density

Initial woody stem density did not differ among the plots (27 stems/m^2, $P = 0.37$). After one growing season, visual observations showed woody stem height to be much lower in M and M+P plots compared to the C and P plots. This trend was observed after the second growing season as well.

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Longleaf Pine Survival

Longleaf pine survival was less than 60 percent for every treatment after the first growing season (table 1). After the second growing season, survival significantly decreased ($P < 0.05$) and was less than 40 percent for every treatment (table 2). In addition, there was no significant difference in survival among the treatments after the first or second growing season ($P > 0.05$).

Longleaf Pine Growth

After one growing season, survival, RCD, HT, and SVI of the longleaf pine seedlings did not differ among treatments (table 1, $P > 0.05$). After the second growing season, there was a slight difference in RCD and SVI among the treatments (table 2, $P < 0.05$). Seedlings in the M+P treatment had slightly higher RCD than seedlings in the M only treatment and slightly greater SVI than all other treatments (table 2). There was no significant difference in growth for any of the variables between the two growing seasons ($P > 0.05$).

Table 1—Survival, root collar diameter (RCD), height (HT), and stem volume index (SVI) of longleaf pine seedlings after one growing season for four treatments: 1) Mechanical woody stem removal (M), 2) P fertilization (P), 3) M+P, and 4) Control (C)

	Survival (%)		RCD (mm)		HT (mm)		SVI (mm^3)	
Treatment	Mean	SE	Mean	SE	Mean	SE	Mean	SE
M	44	13	10.5	0.9	19.9	2.2	2247	662
P	48	12	10.7	0.6	19.1	2.6	2340	494
M+P	56	12	11.2	0.2	19.6	1.7	2602	330
C	59	06	10.8	0.6	18.7	1.2	2401	400

Table 2—Survival, root collar diameter (RCD), height (HT), and stem volume index (SVI) of longleaf pine seedlings after two growing seasons for four treatments: 1) Mechanical woody stem removal (M), 2) P fertilization (P), 3) M+P, and 4) Control (C)

	Survival (%)		RCD (mm)		HT (mm)		SVI (mm^3)	
Treatment	Mean	SE	Mean	SE	Mean	SE	Mean	SE
M	22	07	09.8a[a]	0.4	18.7	3.7	1890a	558
P	33	12	10.7ab	0.5	16.1	1.6	1911a	190
M+P	39	11	11.6b	0.6	19.5	1.8	2903b	545
C	36	10	10.2ab	0.5	15.7	2.3	1800a	590

[a] Letters following means for an individual column indicate a significant difference ($P < 0.05$).

DISCUSSION

In southern flatwoods sites, woody shrub competition and limited nutrient availability can severely reduce pine growth (Colbert and others 1990). In a study of longleaf pine establishment in an abandoned pasture in FL, Ramsey and others (2003) reported that local resource competition was the leading influential factor on longleaf pine seedling growth. In our study, after two growing seasons, SVI of seedlings in the M+P treatment was slightly greater compared to seedlings in other treatments, supporting the data from Ramsey and others (2003). However, it does not appear that in our study resource competition was altered enough to cause longleaf seedling emergence from the grass stage. Furthermore, the overall poor survival of all treatments suggests that additional factors, such as drought, may have influenced seedling growth and survival.

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ASSESSMENT OF THE 1998–2001 DROUGHT IMPACT ON FOREST HEALTH IN SOUTHEASTERN FORESTS: AN ANALYSIS OF DROUGHT SEVERITY USING FHM DATA

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INTRODUCTION

Analyses of forest health indicators monitored through the Forest Health and Monitoring (FHM) program suggested that weather was the most important cause of tree mortality. Drought is of particular importance among weather variables because several global climate change scenarios predicted more frequent and/or intense drought in the Southeastern United States. During the years of 1998-2001, extensive forest areas within the Southeastern United States experienced severe drought conditions (defined by the Palmer Drought Severity Index (PDSI)). In this study, we used FHM data to examine the effect of drought induced moisture stress on forest growth, mortality and changes in crown condition at a regional scale.

OBJECTIVES

Our objective was to investigate changes in growth, mortality, and crown condition across the Southeastern United States under various drought conditions using 1991 to 2005 FHM plot data. Specifically, we examined how drought severity influenced the rates of annual growth, mortality, and change in crown condition using PDSI as an indicator of drought severity. Drought effects were examined for three species groups (pines, oaks, and mesophytic species).

METHODS

FHM plot data from 1991 to 2005 for 307 plots located in AL, GA, and VA were used in this study. Tree data were obtained at the subplot level from a total of 936 subplots. Within each subplot, all trees with diameter at breast height greater than 5 inches were measured. Annual relative growth rate and annual rate of change for crown density, crown dieback, and foliage transparency crown condition indicators were calculated for each tree re-measurement. Annual mortality rates within a subplot were calculated for each species and were expressed as percent removed per year. Monthly PDSI values during the study period were obtained for each of the plots from NOAA. Drought conditions were assigned to each interval of plot measurements based on the minimum growing season (May to September) PDSI using a classification similar to that used by NOAA: 1) no drought, 2) mild drought, 3) moderate drought, and 4) severe drought. Three species groups were identified for analyses: 1) pine (*Pinus*), 2) oak (*Quercus*), and 3) mesophytic species. The mesophytic species group includes maple (*Acer*), birch (*Betula*), beech (*Fagus*), sweetgum (*Liquidambar*), yellow-poplar (*Liriodendron*), and magnolia (*Magnolia*). The mixed model procedure PROC MIXED in the SAS/STAT software was used to examine the relationship between the dependent variables (i.e., the rates of relative growth, mortality, and change in crown condition) and drought severity and stand condition variables. Five stand condition variables were included in the analyses to account for varying stand conditions: total basal area, total tree density, tree species richness, slope, and stand age. The means were calculated for each dependent variable by drought class and species group. The LSD test was used to determine differences among the drought classes for each of the dependent variables.

RESULTS AND DISCUSSION

A general decrease in mean relative growth rate was observed with increasing drought severity. However, mean relative growth rates were not significantly different among drought classes for the oak species group, indicating that oaks exhibit drought tolerance and can maintain growth rates during drought episodes, regardless of drought severity. The pine and mesophytic species exhibited a significant reduction in growth rate when exposed to mild and moderate drought. These findings suggest that oaks can maintain growth rates during drought episodes but pine and mesophytic species cannot. A general increase in mean mortality rate was observed with increasing drought severity for the pine and mesophytic species groups. Mean mortality rates within the no drought class were significantly lower than those within the other three drought classes, among which no significant differences in mean mortality rate were observed, for both the pine and mesophytic species groups. The pine and mesophytic species groups appear to be sensitive to drought and suffer higher mortality rates during drought episodes, regardless of drought severity. However, mean mortality rates were not significantly different among drought classes for the oak species group, indicating that oaks exhibit drought tolerance and can avoid mortality during drought episodes, regardless of drought severity. Our analyses failed to show any negative effect of drought on the change of crown conditions, suggesting that detecting changes in crown condition indicators over a relatively short plot measurement interval using visual measures at 5 percent increments may be unrealistic.

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CONCLUSIONS

(1) Pines and mesophytic species exhibited a significant reduction in growth rate and increase in mortality rate with increasing drought severity, suggesting they are sensitive to drought.

(2) Oaks exhibited no significant change in either growth or mortality rates with increasing drought severity, suggesting that they are tolerant of drought (even under the most severe drought class).

(3) No realistic change in crown condition was observed. Therefore, change in crown condition in relation to drought severity may require different data and/or analyses.

(4) The observed differential growth and mortality rates among different species groups in response to drought severity may alter the composition of Southeastern United States forests if drought episodes become more frequent and/or intense due to climate change. The potential shift in forest composition should be considered in current forest management in order to sustain these forests in the future.

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SIMULATION OF DYNAMICS OF SOUTHERN PINE BEETLE HAZARD RATING WITH RESPECT TO SILVICULTURAL TREATMENT AND STAND DEVELOPMENT

D.J. Leduc and J.C.G. Goelz[1]

Abstract—The hazard of southern pine beetle (SPB) infestations is affected by characteristics such as stand density, stand age, site quality, and tree size. COMPUTE P-LOB is a model that simulates the growth and development of loblolly pine plantations in the west gulf coastal plain. P-LOB was rewritten as COMPUTE SPB-Lob to update it for current operating systems and to incorporate three hazard rating models for SPB. The new program allows a user to simulate the growth of a loblolly pine plantation with different starting conditions and thinning criteria to provide an estimate of growth and yield along with the hazard of SPB infestation. This paper explains how to use this program with its added capabilities of more volume options and triggers that specify thinning by the level of basal area, trees per acre, or SPB hazard. Examples of output that show a range of different stand conditions and treatments are presented.

INTRODUCTION

COMPUTE SPB-Lob is a program written by the first author to predict the growth of loblolly pine (*Pinus taeda* L.) plantations in the West Gulf Coastal Plain of the United States and to predict the associated Southern Pine Beetle (*Dendroctonus frontalis* Zimmermann) hazard rating. Southern pine beetle is an important factor to be considered in management of loblolly pine plantations due to the potentially explosive tree-killing nature of infestations. This new version of COMPUTE SPB-Lob calculates the hazard rating for southern pine beetle and simulates stand development. Additional features of this new program are a choice of output as a text file or an MS Excel® spreadsheet and graphs of the growth and hazard ratings of the predicted stand. The original P-LOB program, on which this new program is based, was written in FORTRAN (Ferguson and Baldwin 1987); the interface and output options no longer meet current standards for computer programs running in the MS Windows® environment. This paper will serve as a user's guide to the new COMPUTE SPB-Lob.

PROGRAM OPERATION

System Requirements

COMPUTE SPB-Lob is a Windows® program; some version of Microsoft Windows 95® operating system or higher is necessary. At least 22 MB of hard disk space for installation of the program and help files is required. When running, the program uses 10 MB of RAM. The onscreen forms were designed to have a resolution of 800 x 600 pixels, but they will scale to other sizes. To get all of the program features, including graphical output, the user must install Microsoft Excel® on his or her computer. Although the program will run without Microsoft Excel®, unless that program is installed, only text output will be provided. Spreadsheets created with this program may well be useable with other compatible software, but the actual Excel® program is needed to create them.

Installation

COMPUTE SPB-Lob is a standard Windows® program, which may be obtained as a ZIP file or on a CD from the lead author. The ZIP file is available at http://www.srs.fs.usda.gov/longleaf/downloads.html. To perform the installation a user opens the ZIP file, double-clicks on setup.exe, and follows the prompts. The CD is designed to start installation automatically. On systems like Windows 2000® and above, administrative privileges are required to install SPB-Lob. The program may be uninstalled using the Add/Remove Programs icon in the Windows® control panel.

Usage

COMPUTE SPB-Lob can be selected and run from the Start menu. This will produce the title screen shown in figure 1. The user can wait 5 seconds or click on the picture to move immediately to the initial parameters screen.

The initial parameters screen (fig. 2) supplies most of the information necessary to begin the simulation. To make this screen easier to explain, numeric tags have been attached to some of the fields in the figure. They are referenced and explained below.

Tag 1 points to the starting and ending age. Both the starting and final age must be at least 10 but no more than 50 years, in multiples of 5 years. The final age, of course, must be greater than or equal to the starting age.

Tag 2 points to a description of site quality, where the user can specify the height of dominant and codominant trees at the initial age given above or can specify a site index and base age of 25 or 50 years. Base age is selected using the radio buttons. To prevent confusion, the program will not accept both a height and a site index; only one can be specified.

Tag 3 points to the section dealing with previous thinning. The user must specify if the stand has been thinned before. If it has not been thinned, information otherwise provided here will be grayed-out. If thinning has occurred, the user must supply the number of thinnings and the stand age when the last thinning occurred. The user also must supply basal area

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in square feet per acre after the last thinning or the surviving number of trees after the last thinning. If both basal area and number of trees are provided, both will be used.

Tag 4 points to the section specifying initial stand density. The user can provide data in terms of surviving trees per acre, current basal area in square feet per acre, or trees planted per acre. If a stand has not been thinned, the user must provide any or all of the following: surviving trees per acre, current basal area per acre, or trees planted per acre. If the stand has been thinned, these data can be omitted. The original FORTRAN version of COMPUTE P-LOB only allowed the user to enter one of these density indicators. This version allows you to enter them all. Bear in mind that it is possible to specify a stand that could not exist in reality and the simulation will be affected by the numbers that you supply. If you enter both basal area and trees per acre, both parameters will be used to create the initial stand table. Trees planted per acre have no effect if either of surviving trees per acre or basal area per acre has been supplied.

Tag 5 points to the section where the user is asked to specify units of volume or weight desired in final output. It is possible to check any, all, or none of these boxes depending on your product interests. There is also a check box (6) to display all possible units. One of the volume units (7), cords, is special because the calculation requires cubic-foot volume. It is simply a conversion from cubic-foot volume so it is disabled if the user does not request the calculation cubic-foot volume. The user can also supply any conversion factor that they want with a default value supplied. This conversion factor is saved like all other parameters, if the user saves the simulation input.

There are three command buttons on this screen. The one labeled "clear all" (8) eliminates entries shown on the screen. The user might want to establish an entirely new scenario. If settings have been saved from a previous COMPUTE SPB-Lob run, there will be one or more INI files stored on the user's computer. Windows® OS remembers the last place that you last saved these files from one program execution to the next. Clicking on the "recover saved options" button (9) will load all of the parameters from the run saved in one of these INI files. This is very convenient if the user wants to do many similar runs of COMPUTE SPB-Lob with only minor variations, or if he/she wants to establish a set of different scenarios for demonstration purposes. To continue with the next input screen of the simulation, click on the continue (10) button.

When a run of COMPUTE SPB-Lob is finished, the user is returned to this screen (fig. 2) and may generate results for another scenario or choose "quit" from the menu at the top of the screen.

The next screen that appears contains three choices, which are checkboxes for the southern pine beetle models that a user may want to run (fig. 3); any or all of the boxes may be checked. If the user chooses the Texas model (1) it will be necessary also to choose a landform, ridge, bottom, or other. Landform actually is more an indicator of moisture regime than a descriptor of true topological position. Ridge refers to drier upland sites; a bottom refers to moist, low-lying pine sites; and other refers to intermediate conditions. For more details on these models see Mason and others (1985).

After all model selections have been made the user can click "continue" or "go back" (The latter selection will return the user to the main parameters screen.).

Clicking "continue" will provide the user with the future thinnings screen (fig. 4). Here one can specify the management of a simulated stand.

Two main parameters affect thinning: the trigger and the target. The trigger (1) is an event that determines if there will be a thinning. The user can choose from six trigger criteria: basal area levels, numbers of trees per acre, stand density

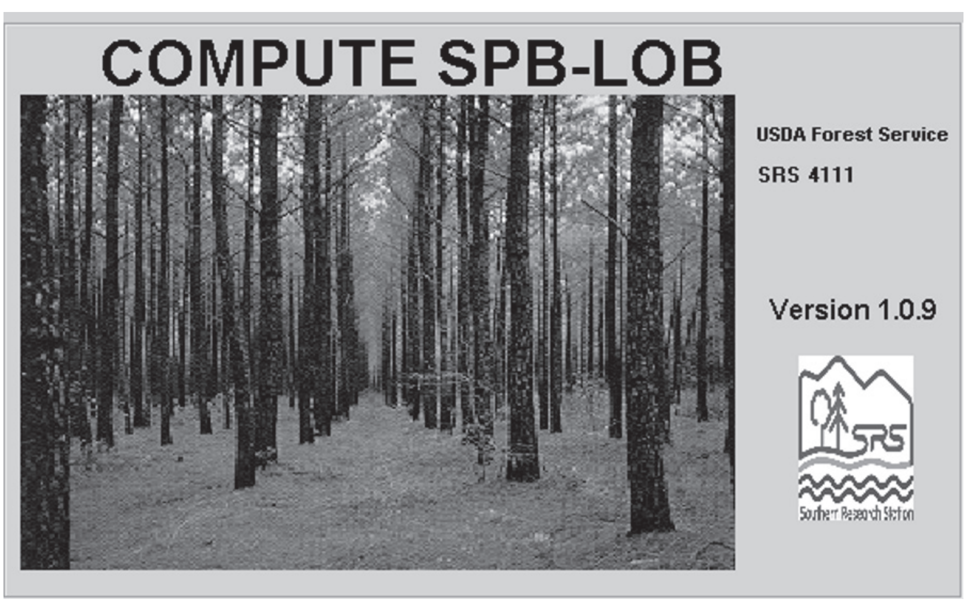

Figure 1—The title screen of the COMPUTE SPB-Lob program.

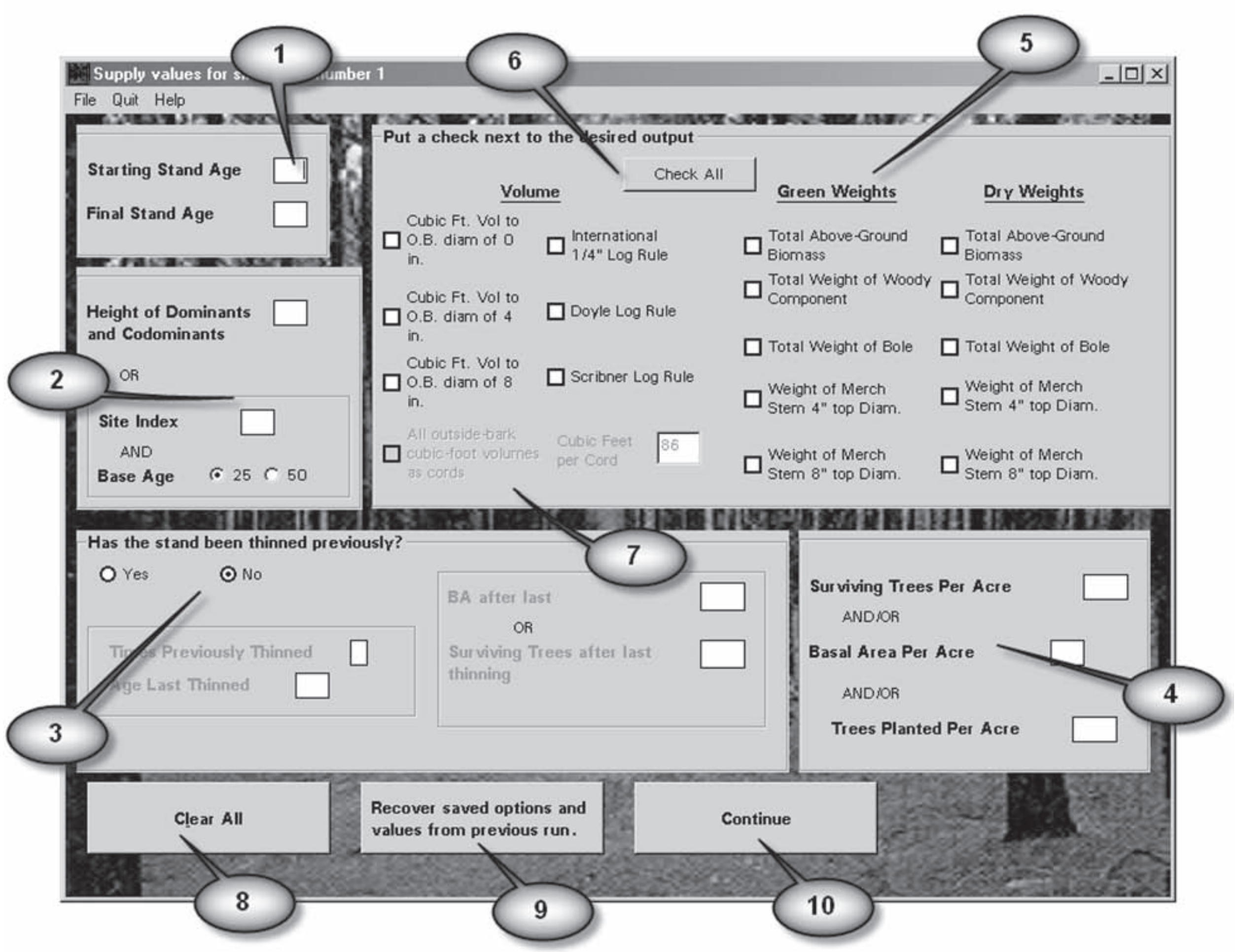

Figure 2—The main information screen for the program. The numbered balloons refer to elements of the screen that are discussed in the text in the usage section.

index, or any of the southern pine beetle hazard ratings (if they have been calculated on the previous screen). Select one of these indicators by clicking on the appropriate model radio button. The target (2) is a goal for the stand after thinning. Any of three target criteria may be used: basal area levels, numbers of trees per acre, or stand density index. Although matching trigger types and target values are not necessary, the user is limited to one type of trigger or target per simulation, which is selected by clicking on the appropriate radio button.

COMPUTE SPB-Lob calculates and shows the simulated stand every 5 years. The user can thin at any of these 5 year intervals by setting a trigger and a target. The thinning will happen if the current value for that variable exceeds the trigger value. For any of the SPB models, the specified hazard level can be met or exceeded. If any of these values are blank or zero for a given age, a thinning will not be considered. It is possible to force a thinning by setting a low value for the trigger that is still above zero. In addition to meeting the thinning trigger, there must also be a low enough value for the thinning target before a thinning is triggered (i.e., if thinning to 300 trees per acre is desired, but there are only 299 trees per acre present, there will be no thinning). Only ages that are part of your simulation will show (3).

There are a few convenience features added to this screen. The column of “clear” buttons (4) allows elimination of a thinning without requiring excessive deletion of on-screen data. The button labeled “copy above” (5) makes it easy to repeat the same trigger and target values for several or all years in the simulation.

Note: if the thinning trigger is any of the southern pine beetle models, the numeric-entry box will change to a list box as shown in figure 5. Use arrows on the right of the box to select the hazard rating, which will trigger thinning. Additionally, the user should be aware that the default method of operation for a Microsoft list box is that you must click on a selection in a list box to make it active. This is not the case for these boxes. Whatever risk level shows is the one that will be used.

Another convenience feature is that all parameters entered in the last three screens can be saved as a starting point for

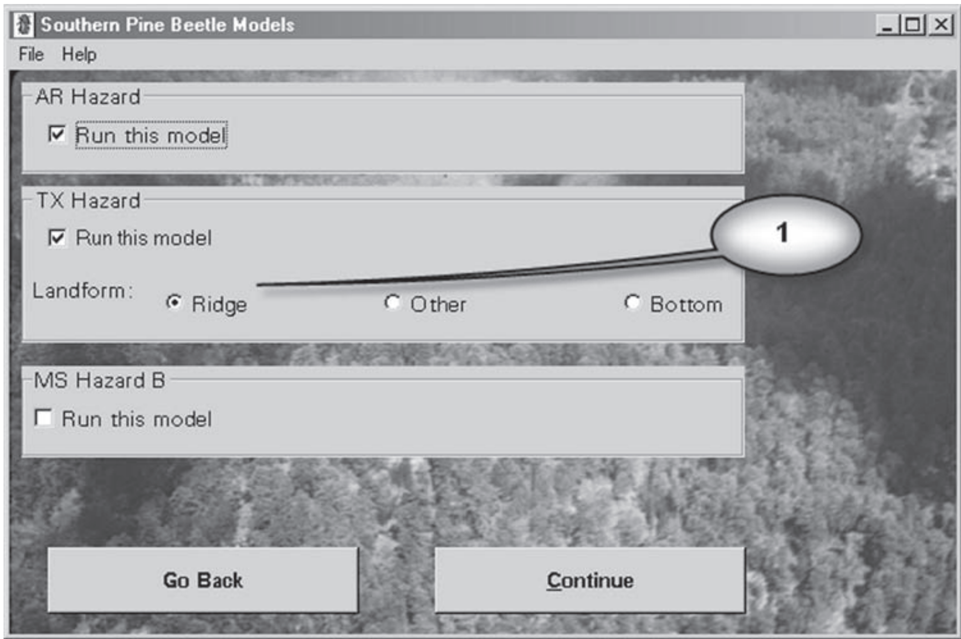

Figure 3—The screen for selecting the southern pine beetle hazard rating models to be calculated. The number in the balloon is referred to in the text in the usage section.

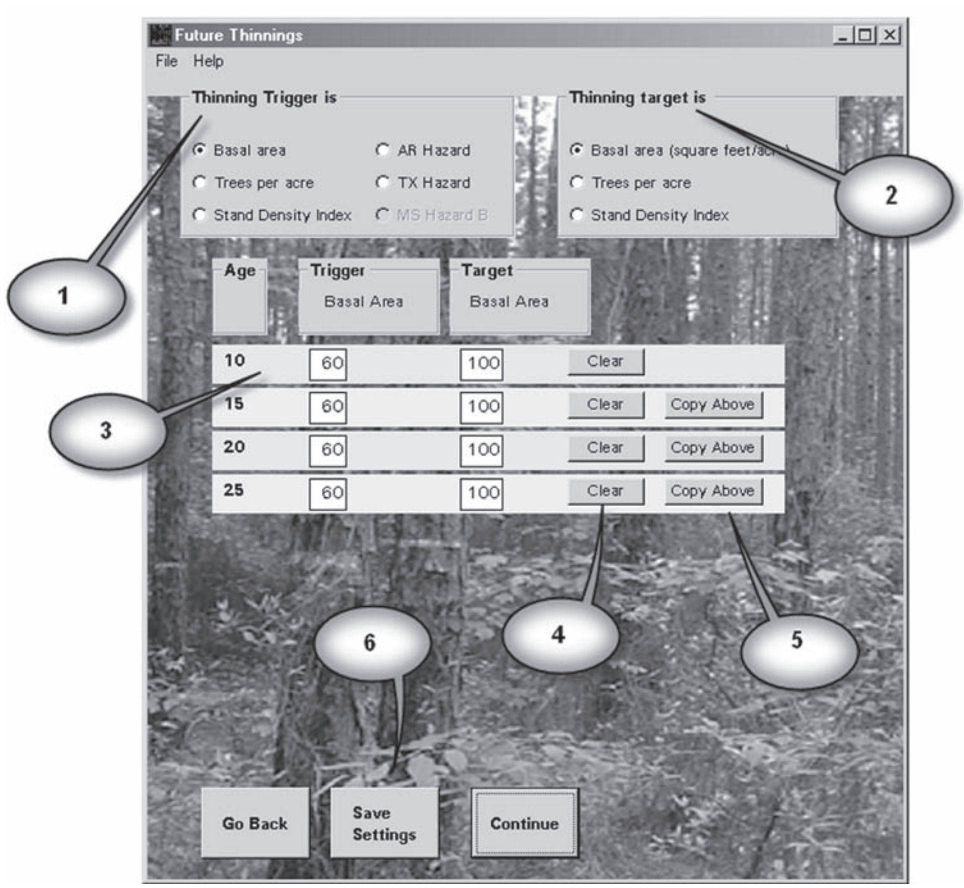

Figure 4—The screen used to select the thinning regime in its default form. The numbered balloons refer to elements of the screen that are discussed in the text in the usage section.

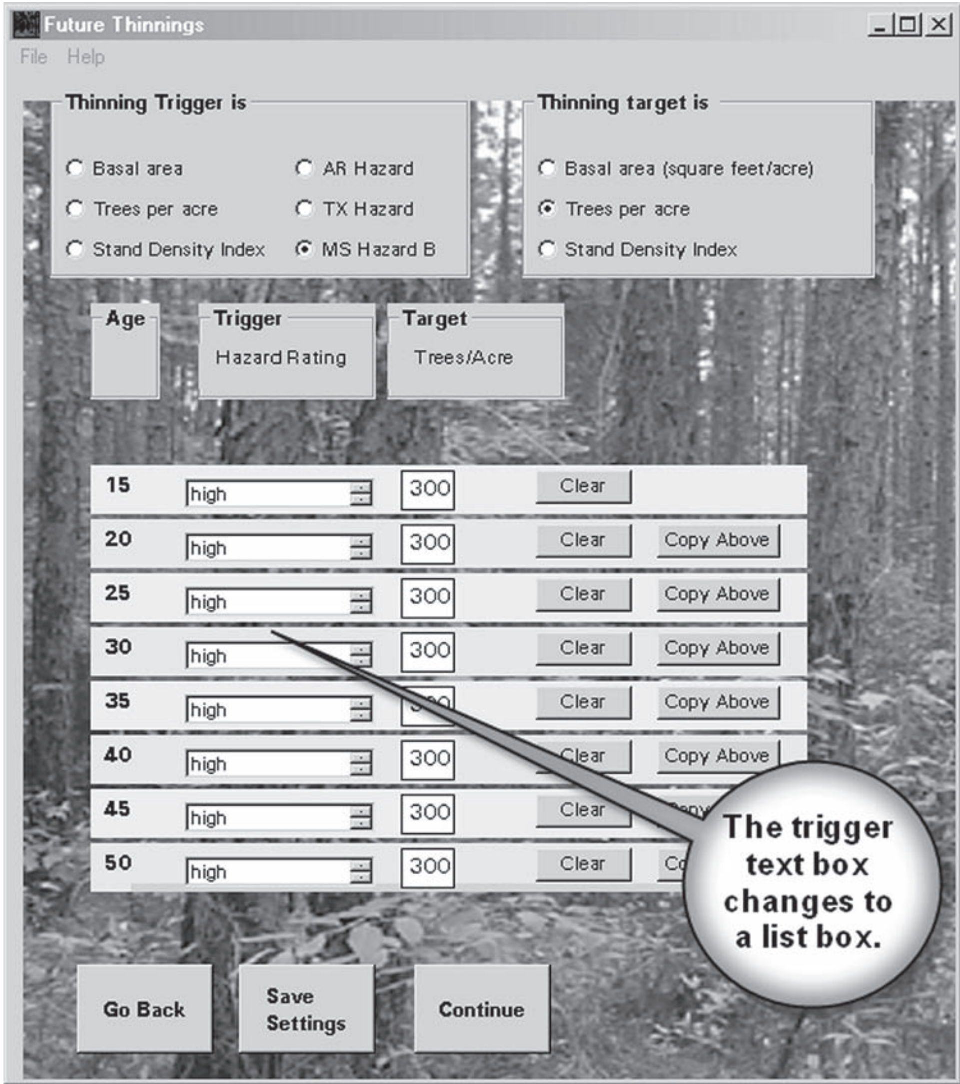

Figure 5—The alternative form of the screen used to select a thinning regime if the thinning triggers are to be based on the hazard rating in a stand. The specific difference between this screen and the default form of figure 4 is highlighted by the balloon.

another simulation. To do this, click on the "save settings" (fig. 4, #6) button, this prompts the user to supply a file name to store the parameters. The default extension is INI for initialization file.

Once the user has clicked the "continue", he/she will be asked to select an output file. The file selection box for output from COMPUTE SPB-Lob is like most file dialog boxes produced by Windows® programs with directory selection at the top, a list of files fitting your pattern in the large middle box, a place to type new files names below this box, and a line for file type below that. The only unique thing about this box is that there are only two output types that can be saved: text files or Excel® spreadsheets. The actual type of output is governed by the file extension. The file extension must be XLS to produce an Excel® file. Any other extension is assumed to be a text file. Text files provide all of the output numbers from the model and run extremely fast. Excel® files, on the other hand, also contain all of the output numbers from the model, but they allow further analysis to be done more easily and generate several graphs of stand development; but are considerably slower to produce.

When the simulation is done, the text file or spreadsheet is opened if you have an appropriate viewer. The main parameter screen (fig. 2) of this program is selected so that you can do another simulation or quit, but it is minimized so that it does not hide the output. An example of the tables produced as text output is shown as figure 6, and the tables produced in the Excel® format are shown in figure 7. Additionally, the Excel® output produces some explanatory graphs like figure 8 for basal area and figure 9 for the Mississippi Hazard B model.

Troubleshooting

We have tried to anticipate problems and prevent them when possible, but have also provided a mechanism for diagnosis. When SPB-Lob runs, it attempts to open a log file in the

```
test.txt - Notepad
File  Edit  Format  Help
COMPUTE SPB-Lob  Version 1.0.5          Tuesday, December 05, 2006  2:03:44 PM
Previously Unthinned Stand
   Trees planted:  800
----------------------------------------------------------------------------------------------------------------------

  Age    15     Thinning Trigger:  Arkansas SPB Hazard Rating at least high             Thinning Target:  Basal Area (sqft/acre) =  80
         Before Thinning Information

  Dominant Height         59.3        Weibull Parameters
  SI(Base Age 25)         80.0        A=       2.003
  Quadratic Mean DBH       7.536      B=       5.931
  93rd Percentile         10.         C=       3.273
  Stand Density Index    354.8
--------------------------------------------------------------------------------------------------------------------------------------

                                                            Cubic-foot Volume
                                                                per Acre                                                  --------------
                                       Average  ----------------------------------------------------------  Int. 1/4"   Doyle    Scribner   Total      T
   DBH       Stems      Basal     Total      0-inch top          4-inch top          8-inch top        Log Rule  Log Rule  Log Rule   Above      (
  Class       per       Area     Height  ------------------  ------------------  ------------------  8-In. top 8-In. top 8-In. top  Ground     -----
 (inches)    acre    (sqft./ac.)  (feet)    o.b.      i.b.      o.b.      i.b.      o.b.      i.b.   (bdft./ac.)(bdft./ac.)(bdft./ac.)(lbs./ac.)  o
--------------------------------------------------------------------------------------------------------------------------------------
      2       0.2        0.0      23.9       0         0         0         0         0         0         0         0         0          3
      3       6.0        0.3      35.6       6         4         0         0         0         0         0         0         0        334
      4      25.8        2.3      43.2      52        39         0         0         0         0         0         0         0       3038      2
      5      58.9        8.0      48.5     204       156       134        98         0         0         0         0         0      12027     11
      6      94.9       18.6      52.2     500       389       419       320         0         0         0         0         0      30078     28
      7     116.8       31.2      55.0     869       684       797       622         0         0         0         0         0      53299     49
      8     111.0       38.7      57.2    1106       877      1056       834         0         0         0         0         0      69223     64
      9      80.3       35.5      58.9    1031       822      1004       799       445       336         0         0         0      65867     61
     10      43.1       23.5      60.2     691       554       680       544       414       321      1751       686      1408      45104     41
     11      16.6       10.9      61.3     324       261       321       258       234       184      1010       440       831      21616     20
     12       4.4        3.4      62.2     103        83       102        82        83        66       364       167       296       7005      6
     13       0.8        0.7      63.0      21        17        21        17        18        15        81        41        68       1476      1
     14       0.1        0.1      63.7       3         2         3         2         3         2        12         6        10        207
--------------------------------------------------------------------------------------------------------------------------------------
Total       558.6      173.3              4911      3888      4537      3577      1196       923      3218      1341      2613     309277    288
--------------------------------------------------------------------------------------------------------------------------------------


Southern Pine Beetle Hazard Rating Results:
The AR Hazard Score is -49 which is interpreted as High.
The MS Hazard B score is 291 which is interpreted as Very High.
The TX Hazard for a ridge site is Medium.  This means the the 5-year loss projection is 0.007 spots/ac.
or 0.135 trees/ac. with live beetles.

  Age    15         After Thinning Information

  Dominant Height         59.3        Weibull Parameters
  SI(Base Age 25)         80.0        A=       2.465
  Quadratic Mean DBH       7.899      B=       5.835
  93rd Percentile         10.407      C=       3.174
  Stand Density Index    161.
--------------------------------------------------------------------------------------------------------------------------------------
```

Figure 6—An example showing how part of text output may look. The ripped-edge is used to show that the actual file is larger than the figure shows it to be.

directory where it is running. In this log file, program events are recorded as they happen. It is possible to use this file to diagnose potential problems, or, more likely, to help the author in debugging the program. If the log file cannot be opened, the program will run normally without a log file.

One problem that was anticipated, but which may still confuse the user, is the program's inability to calculate a set of Weibull parameters to model the diameter distribution for some specified stands. If this occurs, an error message box will appear (see fig. 10). After clicking OK, the user will be returned to the initial parameters screen to correct input data. The Weibull distribution is calculated based on minimum d.b.h., the quadratic mean diameter, and the diameter at the 93rd percentile. In turn, these parameters can be based on the number of surviving trees, the height of dominant and codominant trees, the thinning basal area, the age, and the number of times the stand has been thinned. To proceed, the user must adjust any such stand parameters. It is quite possible that the exact stand cannot be simulated, and the user may have to use parameters or data that are reasonably close.

RESULTS

A nearly infinite number of possibilities exist for simulating the growth of loblolly pine in plantations that are managed under different thinning regimes. Figure 11 is a collection of four related simulations showing how some management decisions and stand characteristics affect the SPB hazard in terms of the Mississippi Hazard B rating. All of the lines show the stand from age 10 to age 50. Varying choices were made for site index, number of trees planted, and thinning trigger. In all cases thinning was to 80 square feet of basal area. Lines (a) through (c) are all thinned when a high hazard condition is present. The first thinning occurs at a different age for each, and subsequent thinnings occur at 10 to 15 year intervals. Line (a) represents a lower site quality, and captures the fact that the first thinning occurs later than on other site types. Line (b) differs from line (c) in that fewer trees were planted in the former, and it would take 5 years longer to achieve a high-hazard condition. Line (d) is thinned when basal area reaches 100 square feet regardless of the hazard rating. This stand doesn't develop as high a hazard rating as the other stands, but the stand requires two more thinnings than the others. These scenarios show how small parameter changes affect the susceptibility of a stand to SPB-caused losses, but one might also consider how having an estimate of SPB hazard can help optimize management when SPB is a concern.

COMPUTE SPB-Lob Version 1.0.7 Wednesday, March 07, 2007 1:32:25 PM

SI (Base Age 25)= 0 Previously Unthinned Stand

Surviving trees: 500 Current basal area: 80.

Age= 15 **No Thinning This Year**

Thinning Trigger: Trees per acre > 500.

Thinning Target: Trees per Acre = 500.

Dominant Height= 40.0

Quadratic Mean DBH= 5.416

93rd Percentile= 7.743

Stand Density Index= 186.9

Weibull Parameters

A= 1.581

B= 4.042

C= 2.319

DBH Class (inches)	Stems per acre	Basal Area (sqft./ac.)	Average Height (feet)	Scribner Log Rule Vol.	Green Weight of Merch. Stem 8 inch Top Diam.		Dry Weight of Merch. Stem 8 inch Top Diam.	
					o.b.	i.b.	o.b.	i.b.
2	15.8	0.35	17.7	0	0	0	0	0
3	65.5	3.22	26.3	0	0	0	0	0
4	106.1	9.26	32.0	0	0	0	0	0
5	115.4	15.73	35.9	0	0	0	0	0
6	93.8	18.42	38.7	0	24	18	20	12
7	59.0	15.75	40.7	0	662	550	432	296
8	28.9	10.10	42.3	0	1963	1695	1113	811
9	11.1	4.92	43.6	0	2023	1777	1061	796
10	3.3	1.82	44.6	74	1121	993	561	427
11	0.8	0.52	45.4	26	399	355	194	149
12	0.2	0.13	46.1	8	114	102	55	42
Total	500.0	80.22		108	6306	5489	3436	2534

Southern Pine Beetle Hazard Rating Results:

The MS Hazard B score is 51 which is interpreted as Low.

Age= 20 **Before Thinning Information**

Thinning Trigger: Trees per acre > 450.

Thinning Target: Trees per Acre = 450.

Dominant Height= 47.6

Quadratic Mean DBH= 6.768

93rd Percentile= 8.901

Stand Density Index= 241.7

Weibull Parameters

A= 1.914

B= 5.209

C= 3.331

			Average	Scribner	Green Weight of Merch.	Dry Weight of Merch.

Figure 7—An example of some output shown in spreadsheet form. The ripped-edge is used to show that the tables continue down the page. This page is only one of several sheets that can be generated in spreadsheet output.

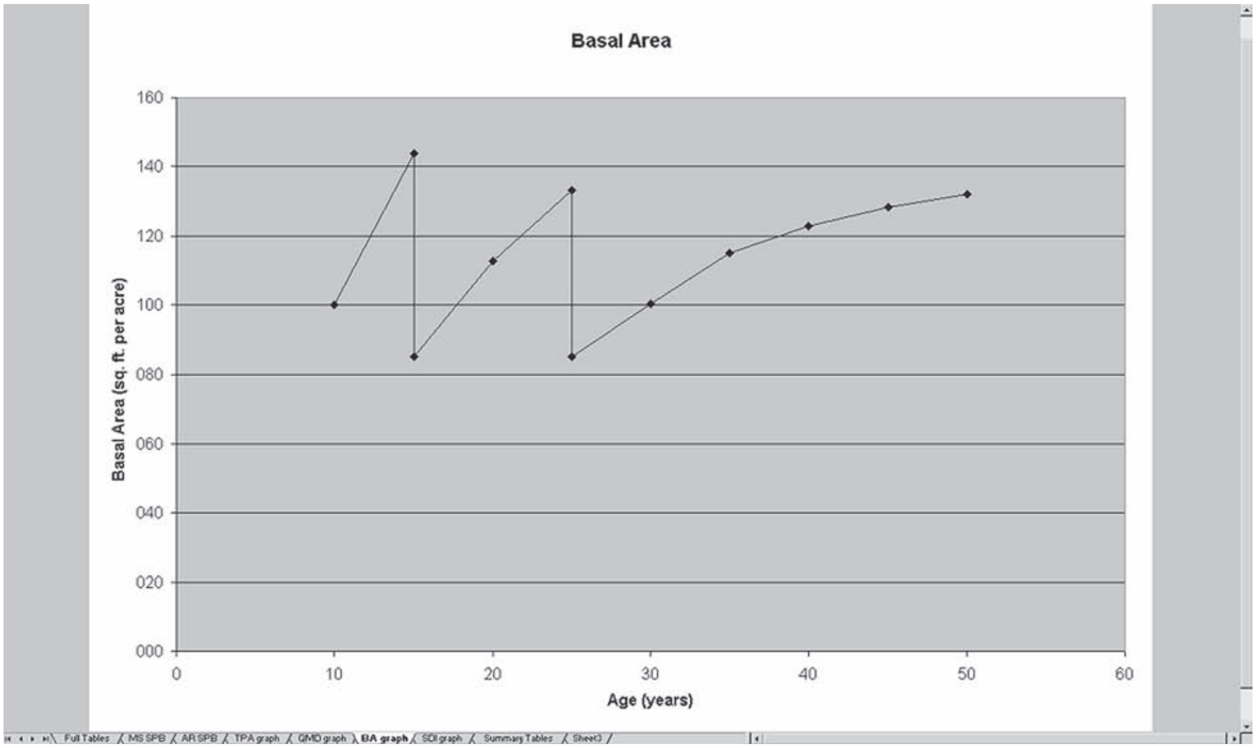

Figure 8—An example of a basal area graph from spreadsheet output. This is only one of several sheets in the spreadsheet output; at the bottom of the figure appear tabs for the other sheets.

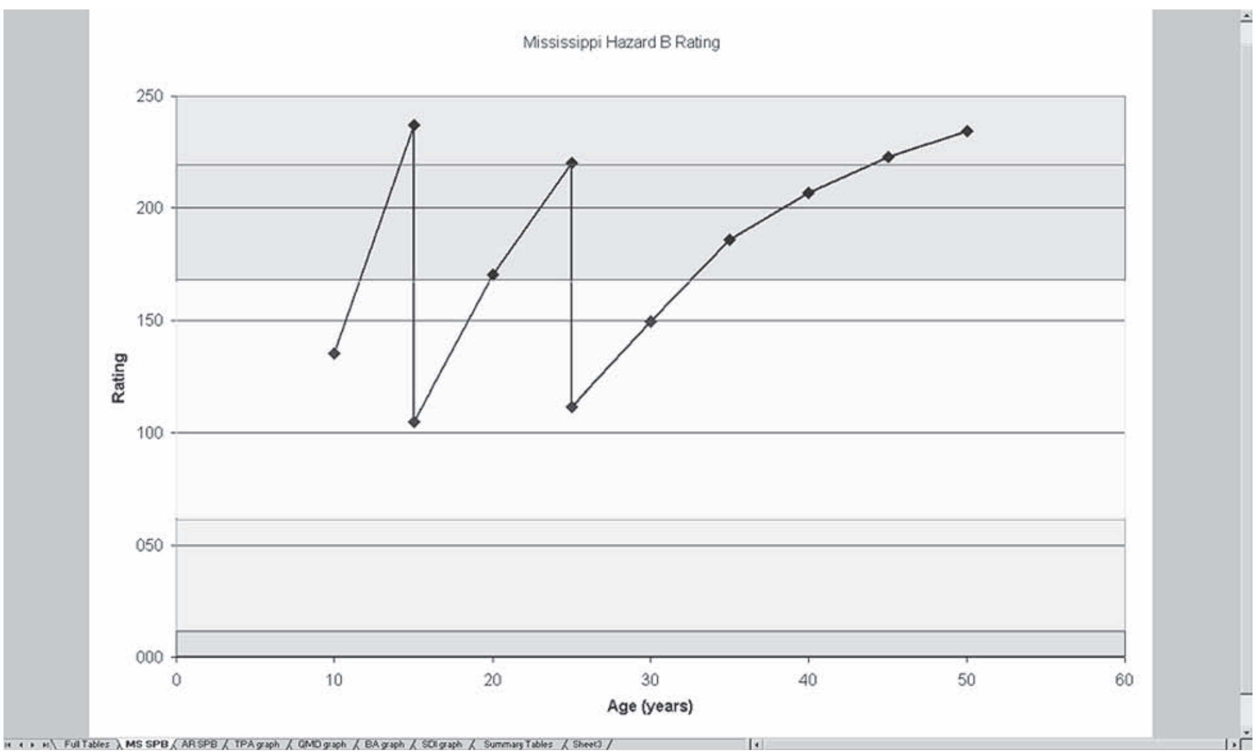

Figure 9—An example of a Mississippi Hazard-B rating graph from the spreadsheet output. This is only one of several sheets in the spreadsheet output; at the bottom of the figure appear tabs for the other sheets. While not obvious in this grayscale version, regions representing different hazard ratings are shaded to indicate the hazard level (i.e., red=high, green=low).

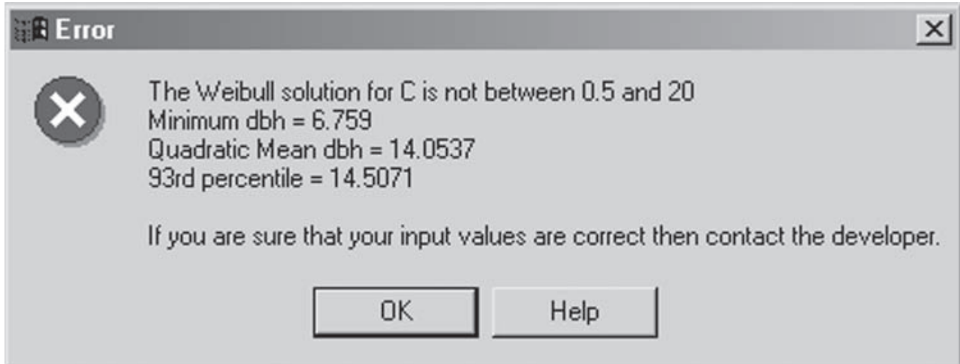

Figure 10—The error message box produced when SPB-Lob cannot calculate a set of Weibull parameters for a stand diameter distribution.

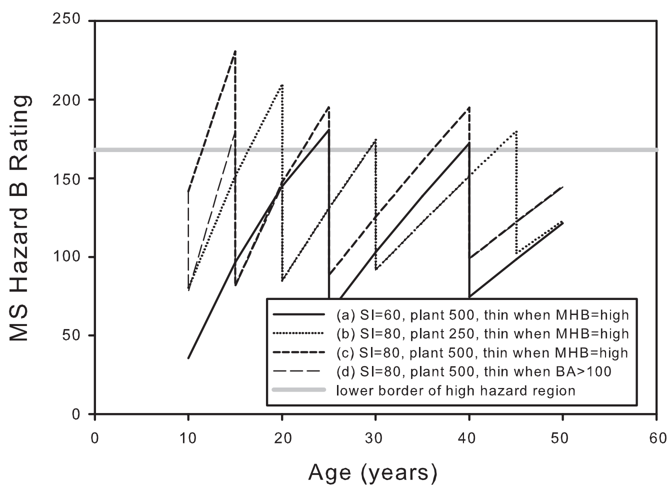

Figure 11—The Mississippi Hazard B rating (MHB) over the treatment life of four simulated stands. Line (a) has site index (base age 25) of 60, with 500 trees planted per acre, and was thinned to a basal area of 80 square feet whenever MHB achieved a high level; line (b) has site index (base age 25) of 80, with 250 trees planted per acre, and was thinned to a basal area of 80 square feet whenever MHB achieved a high level; line (c) has site index (base age 25) of 80, with 500 trees planted per acre, and was thinned to a basal area of 80 square feet whenever MHB achieved a high level; line (d) has site index (base age 25) of 80, with 500 trees planted per acre, and was thinned to a basal area of 80 square feet whenever the basal area exceeded 100 square feet per acre. The horizontal gray line marks the lower boundary of the MHB high rating.

CONCLUSIONS

We could present many other simulations scenarios, but individual land managers can find those which would most consistently address their needs. This program is available online. We welcome input from those who choose to test this new simulation tool. The program is a revision of the COMPUTE-PLOB, a program that was written about 20 years ago. It has an improved interface and, more importantly, makes it possible to see how management actions affect the southern pine beetle hazard. Nonetheless, it is based on a 20 year old model (Baldwin and Feduccia, 1987) for stand growth and with SPB risk models that are at least 16 years old. Its greatest potential for development will be realized as the model is updated with more recently collected data and, possibly, with insect models that better reflect stand conditions found today in the west gulf region.

ACKNOWLEDGMENTS

We acknowledge the financial support of Southern Research Station RWU-4105, which funded development of this program. We extend thanks also to Jason Waltman—a summer student who laid the groundwork for this revision—as well as the many people who tested the program and made suggestions, especially James Meeker and Timothy Haley of the Alexandria Field Office of Forest Health Protection.

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USING BEHAVEPLUS FOR PREDICTING FIRE BEHAVIOR IN SOUTHERN APPALACHIAN HARDWOOD STANDS SUBJECTED TO FUEL REDUCTION TREATMENTS

Helen H. Mohr, Thomas A. Waldrop, and Dean M. Simon[1]

Abstract—There is a crucial need for fuel reduction in United States forests due to decades of fuel accumulation resulting from fire exclusion. The National Fire and Fire Surrogate Study (FFS) addresses this issue by examining the effects of three fuel reduction treatments on numerous response variables. At an FFS site in the southern Appalachian Mountains, fuels were altered by burning, mechanical treatment, and a combination of burning and mechanical treatment. Each treatment produced a unique fuel complex and altered microclimate for surface fuels by opening stands to wind and light. Treatments were designed to minimize potential wildfire damage although fire behavior is difficult to predict. BEHAVEPlus fire modeling system (Andrews and others 2004) was used to compare predicted fire behavior among treatments based on actual fuel and weather data from the site. These data were used to simulate wildfire behavior during extreme weather conditions in the southern Appalachian fire season. Mechanical only treatments had the tallest flame and scorch heights and fastest rate of spread. Burn treatments had lower fire intensities but the mechanical + burn treatment had the lowest fire intensities of the three treatments. These results could be short-term with continued burning and fuel decomposition.

INTRODUCTION

Excessive amounts of fuel have accumulated in southern Appalachian forests over past decades due to fire suppression. North Carolina annually suppresses about 4,700 wildfires averaging 20,000 acres. Application of fuel-reduction treatments in the southern Appalachians are limited, especially prescribed fire. There has been little study of fuel reduction treatments and how they relate to wildfire.

Many land managers in the southern Appalachians have an immediate need to reduce hazardous levels of forest fuels but limited choice of effective techniques. Western United States studies by van Wagtendonk (1996) and Stephens (1998) found that prescribed fire reduced severe fire behavior more than thinning. Stephens (1998) also found that thinning followed by prescribed burning at 95th percentile weather conditions would not produce extreme fire behavior. Brose and Wade (2002) suggest combining treatments for the most effective reduction of hazardous fuels and maintaining ecosystem health in pine flatwood forests. This study is the first to examine wildfire behavior in several fuel reduction treatments in the southern Appalachians.

Fuel reduction treatments at the southern Appalachian site followed National FFS protocols and included prescribed burning, mechanical treatment and a combination of mechanical treatment followed by prescribed burning. These treatments change the fuel complex and microsite climate differently, which could produce different wildfire intensities and severities. Using fuels data, weather data from the 12 treatment areas and extreme fire weather variables we developed custom fuel models to determine if the fuel-reduction treatments had an impact on fire behavior.

National Fire and Fire Surrogate Study

This national study compares ecological and economic impacts of fuel-reduction treatments. It includes 13 sites across the United States where fire has played an historical role. The areas are characterized by excessive fuel buildup and are considered to be at-risk of wildfire. Eight sites are located in the Western United States, and five are in the eastern States. We followed the same protocols on each site both for the treatments themselves and for data collection, which helped us build a national database using core variables.

Location

The southern Appalachian Fire and Fire Surrogate study is located on the Green River Game Lands in Polk County, NC. The overstory is primarily mixed oak-hickory with some yellow pines and a well-developed shrub layer of mountain laurel (*Kalmia latifolia*), rhododendron (*Rhododendron* spp.), and blueberry (*Vaccinium* spp.).

METHODS

The study design was a randomized complete block consisting of three blocks of four treatments; burn only, mechanical only, mechanical + burn, and control. Each was replicated three times. Treatments were 10-ha areas marked by 40 points on a 50 x 50 m grid arranged in a north-south and east-west orientation. At grid points fuel data were collected on three fuels transects using Brown's Planar Intersect Method (Brown 1974) where 1, 10 and 100 hour fuels, as well as fuel height, were measured. These data were used to develop fuel models in the BEHAVEPlus3 fire modeling system (Andrews and others 2004).

HOBO® Micro Station weather stations were placed in a central location within each treatment area to compare microsite differences. Each weather station collected temperature, relative humidity, and wind speed on a 10-min interval. Three additional HOBO® Micro Stations were placed in open clearcuts near treatment areas. These units collected temperature, relative humidity, wind speed, and rainfall on a 10-min interval. The weather data were downloaded onto a laptop computer in the field once every three weeks from September 1, 2006 to December 31, 2006.

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We developed regression equations to predict stand weather conditions based on weather reported at the closest weather base station at Asheville Regional Airport in Asheville, NC. Those equations were used to estimate the high temperature, low relative humidity, and high mid-flame wind speed that would occur in each treatment area on an 80th percentile day during the fire season. We used the predicted weather variables as input in BEHAVEPlus3 to simulate fire behavior in each treatment.

RESULTS

Fuel Loads

Mechanical treatment has increased 1, 10, and 100 hour fuels each year over the last 6 years (fig. 1). Burning increased fuels slightly for the 1, 10, and 100 hour fuels. Mechanical + burn treatments have reduced the 1 and 10 hour fuels. The 100 hour fuels in the mechanical + burns have steadily increased over the last 6 years. Shrubs are most abundant in the control sites with over 6 tons per acre and much less abundant in the mechanical + burn sites with less than 1 ton per acre.

Weather Conditions

Ambient temperature was highest in the burn treatments and lowest in the mechanicals (fig. 2). Relative humidity was lowest in the burn and mechanical + burn treatments (fig. 3). The highest mid-flame wind speeds were in mechanical treatments at around 4 mph (fig. 4). Mechanical + burn treatments had the lowest wind speed of 1.5 mph.

Wildfire Behavior

BEHAVEPlus3 shows that a wildfire would produce the tallest flame lengths in mechanical treatments where large amounts of brush were left after treatment and least in the mechanical + burns (fig. 5). Rate of spread was slowest in mechanical + burn sites which contained the least amount of 1 and 10 hour fuels (fig. 6). Scorch heights were tallest in mechanical sites which had the highest fuel loading for 1, 10, and 100 hour fuels (fig. 7).

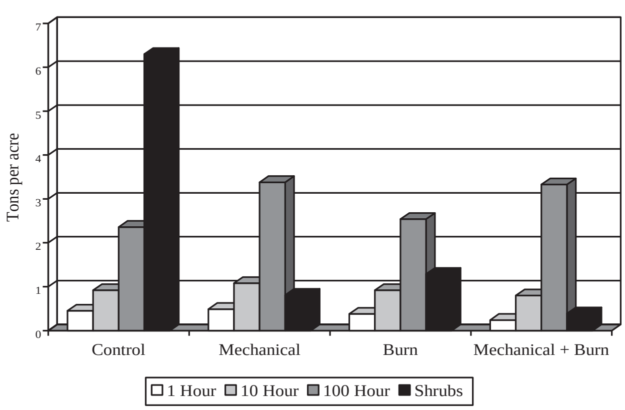

Figure 1—Average fine woody fuels and shrubs in tons-per-acre on all treatments post-treatment.

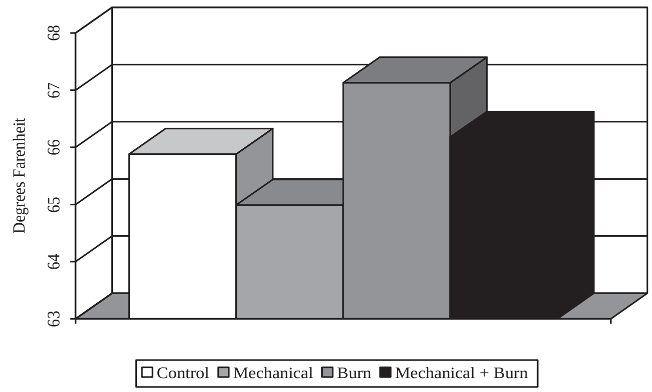

Figure 2—Maximum ambient temperature in degrees Fahrenheit post-treatment.

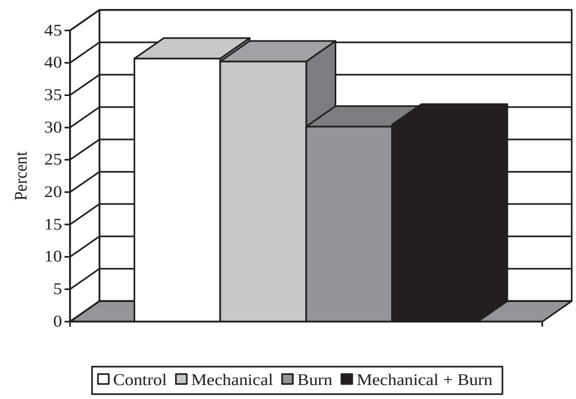

Figure 3—Lowest percent relative humidity post-treatment.

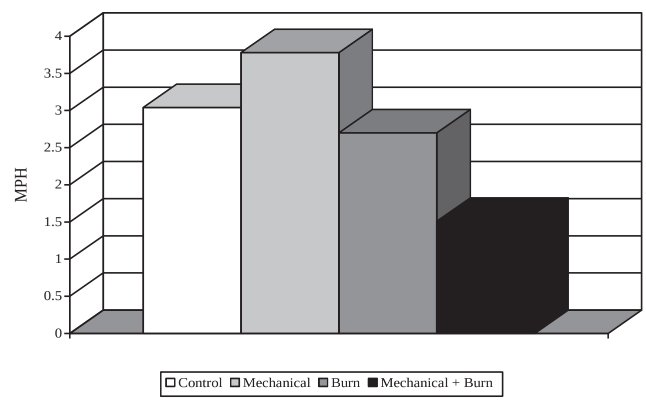

Figure 4—Maximum wind speed in miles per hour post-treatment.

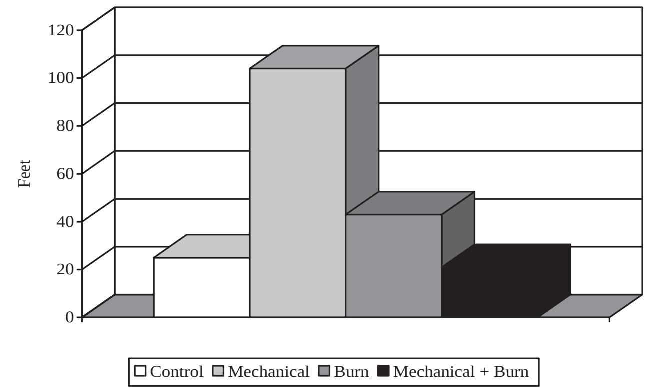

Figure 5—Maximum simulated flame length post-treatment in feet by BEHAVEPlus3.

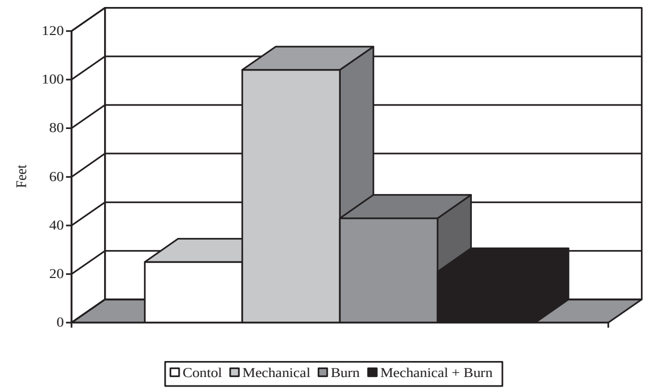

Figure 6—Maximum simulated scorch height in feet post-treatment by BEHAVEPlus3.

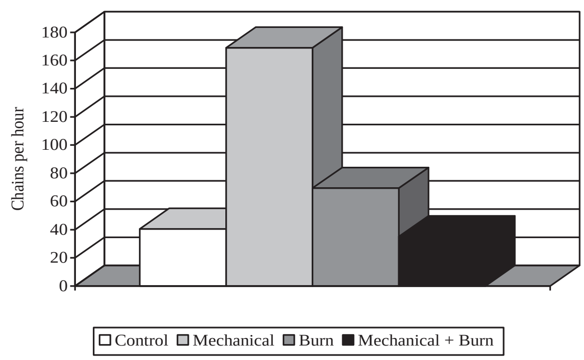

Figure 7—Maximum simulated rate-of-spread post-treatment in chains per hour by BEHAVEPlus3.

DISCUSSION

Mechanically treating then burning as a fuel reduction treatment was the best at reducing wildfire damage on the Southern Appalachian Fire and Fire Surrogate site. Continued burning of these sites will have to occur over the long term to keep fuels from building up to high levels, therefore increasing the chance of wildfire. The burn treatments may decrease fuels if burning continues over the long term. With continued data collection and treatments on the Fire and Fire Surrogate study we will be able to more clearly see the ecological impacts of repeated treatments.

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EFFECTS OF FIRE SEASON ON VEGETATION IN LONGLEAF PINE (*PINUS PALUSTRIS*) FORESTS

Bryan T. Mudder, G. Geoff Wang, Joan L. Walker, J. Drew Lanham, and Ralph Costa[1]

Forest managers in the Southeastern United States are interested in the restoration of not only longleaf pine (*Pinus palustris*) trees, but also the characteristic forest structure and ground-layer vegetation of the longleaf pine ecosystem. Season of burn, fire intensity, and fire frequency are critical components of a fire regime that supports diverse ground layer vegetation and an open midstory. While some previous studies have concluded that a change to growing season burning for long periods of time (decades) facilitates restoration, such a change may be undesirable, especially for private land managers with more immediate management objectives, such as improving habitat for quail. There is a need to document short-term benefits associated with a change from dormant- to growing-season burning.

We investigated the short-term effects of a change from dormant- to growing-season prescribed burns on the abundance, structure, and composition of vegetation at Brosnan Forest in the mid-Atlantic coastal plain of SC. Fifty-two experimental units (EU's), approximately 40-ha in size, were used. Thirty-two randomly selected units were burned during the dormant season (January to March), and 20 were burned during the growing season (April to September) of 2001, 2003, and/or 2004. We tallied the number of woody stems ≥ 1 m tall in 6 to 12 randomly selected 5 by 5 m sampling plots per EU. In each of four 1 by 1 m subplots located in the corners of each sampling plot we recorded the percent cover of seven vegetation classes: wiregrass, other graminoids, cane, ferns, forbs, legumes, and woody plant species. The sub-plot mean was used for analysis.

Analysis of variance indicated that the growing season burn plots had significantly ($p \leq 0.05$) greater ground cover of species within the wiregrass (*Aristida beyrichiana*), cane (*Arundinaria gigantea*), other graminoids, and legume vegetation classes (table 1). Time since the last burn (p

Table 1—ANOVA: effects of fire season on vegetation abundance. Time since last burn (TLAST) was used as a covariate when significant.

Life form group	Source	Sum of square error	Degrees of freedom	Mean square error	F-statistic	P-value
Wiregrass	Season	59.517	1	59.517	4.707	0.035
	Error	632.155	50	12.643		
Other grasses	Season	189.865	1	188.904	8.001	0.007
	Error	1185.062	50	23.701		
Legumes	Season	12.959	1	12.959	9.684	0.003
	TLAST	5.463	1	5.463	4.082	0.049
	Error	65.574	49	1.338		
Cane	Season	9.879	1	9.879	10.121	0.003
	Error	48.804	50	0.976		
Woody	Season	471.736	1	471.736	3.925	0.053
	Error	6008.955	50	120.179		
Herbs	Season	11.789	1	11.789	1.491	0.228
	Error	395.444	50	7.909		
Ferns	Season	469.517	1	469.517	3.028	0.088
	Error	7752.287	50	155.046		
Number of woody species 1m tall	Season	4.441	1	4.441	5.858	0.019
	TLAST	18.520	1	18.520	24.426	0.000
	Error	37.152	49	0.758		

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≤ 0.05) was significant as a covariate only in the analysis of legume data. Plots burned in the dormant season had significantly ($p \leq 0.05$) more cover of woody vegetation, a higher diversity of woody species ≥ 1 m tall, and a greater number of woody stems ≥ 1 m tall (table 1). Nonmetric multidimensional scaling indicated no clear patterns in compositional response as related to season of burn.

The growing season burns during 5 years promoted an abundance of several desirable life form classes while inhibiting the development of undesirable woody vegetation. These beneficial effects of growing season burns, promoting desirable ground layer vegetation and an open midstory, will interest landowners whose objectives include management for wildlife. Incorporating a few growing season burns over a short time period can provide these benefits while increasing flexibility in the landowner's use of prescribed fire as a management tool.

EFFECTS OF FOREST FIRE AND LOGGING ON FOREST DEGREDATION IN MONGLIA

Yeong Dae Park, Don Koo Lee, Jamsran Tsogtbaatar, and John A. Stanturf[1]

Abstract—Forests in Mongolia have been severely degraded by forest fire and exploitive logging. This study investigated changes in vegetation and soil properties after forest fire or clearfelling. Microclimate conditions such as temperature and relative humidity (RH) changed drastically after forest fire or logging; temperature increased 1.6-1.7 °C on average, whereas RH decreased up to 15.7 percent after logging. Thus, burned and logged stands became drier and it mainly affected understory species composition such as the succession of steppe xerophytes from taiga and meadow mesophytes. Soil moisture significantly decreased after forest fire or logging, and the extent of decrease was more severe in the logged stand. The chemical properties of the organic layer were significantly changed, more so than the properties of the mineral soil horizons.

INTRODUCTION

Forest degradation is one of the main environmental concerns globally because degradation constrains environmental functions of forests (Daily and Ehrlich 1995, Burley 2002). Global attention to forest degradation in northeast Asia including the Russian Far East, China, Mongolia and the Democratic People's Republic of Korea (DPRK), has been greatly heightened by dramatic changes in climate in recent years (Lee and Park 2001). Forests in Mongolia have been severely degraded by wildfire and exploitive logging (World Bank 2002, Tsogtbaatar 2004), and this degradation has negatively affected the environment of neighboring countries including Korea. Between 1971 and 1997, approximately 2,700 large- and small-scale fires occurred and destroyed over 14 million ha of forests. Particularly in 1997, 2.7 million ha burned (FAO, 2001). During the last decade, Mongolia lost approximately 4 million ha of forests, averaging 40,000 ha annually but between 1990 and 2000, the rate of deforestation increased to 60,000 ha/year. As a result of this ongoing loss and degradation, 1.6 million ha of forest area has been completely lost between 1974 and 2000 due to fire, improper clearfelling, overgrazing, and mining activities (UNEP, 2002). The objectives of this study were (1) to investigate the changes in vegetation and soil properties after forest fire or clearfelling, and (2) to discuss the effects on forest degradation and future restoration work in Mongolia.

MATERIALS AND METHODS

The field study was conducted at southern area of Khenti in Mongolia, which lies between the southern fringe of the Siberian boreal forest and the Mid-Asia Steppe zone. This area is very sensitive and vulnerable to external disturbances such as forest fire and logging. A total of 17 study sites were selected: six for reference sites, seven for burned sites, and four for clearfelled sites. In each site, three 30 by 30 m square plots were randomly established to investigate the composition of overstory species. In each main plot, three 5 by 5 m square subplots were established to investigate natural regeneration and five 2 by 2 m square subplots were included to investigate the composition of understory vegetation. For all identified vegetation, we calculated importance value, species diversity, and similarity in order to examine the changes in vegetation after forest fire or logging. In each main plot, soils were sampled using a soil auger at three soil depths: the forest floor (O) and two mineral horizons (A and B), with four replications for each horizon. All samples were air-dried after collection and analyzed for physical and chemical properties such as moisture content, pH, soil texture, organic matter, nitrogen, phosphorous and cation exchange capacity (CEC). Three portable HOBO data loggers were launched in each stand to collect daily mean temperature and relative humidity at one-hour intervals. The differences in vegetation and soil properties among the study plots were determined by analysis of variance (ANOVA) using Tukey's Studentized Range to test separation of means (SAS 8.2). The significance for all analyses was set at α=0.05.

RESULTS AND DISCUSSION

Changes in Vegetation Composition after Forest Fire or Logging

Stand development and natural regeneration—The patterns of stand development after fire or clearfelling in *Larix sibirica* stands mainly progressed in four stages: (1) secondary *Larix sibirica* stand, (2) hardwood stand mainly composed of birch (*Betula* spp.) and willow (*Salix* spp.), (3) bush stand, and (4) grassland (steppe). Stand development strongly depended on the intensity of degradation and the potential for natural regeneration (Oliver and Larson 1996). The intensity of degradation in secondary larch and hardwood forests was slight after forest fire and these forests progressed easily into a natural regeneration stage with more than 5,000 seedlings/ha. The bush stand and steppe, however, were affected by severe degradation after clearfelling, and progressed slowly into, or did not reach the natural regeneration stage; there were less than 100 seedlings/ha. Natural regeneration usually occurs more readily on burned as opposed to logged sites as a result

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of initial competition, with or without understory vegetation (White 1979). Thus, rehabilitation is needed more urgently after logging than after wildfire.

Changes in understory composition—The number of species was not significantly changed after logging but significantly increased after forest fire (fig. 1). Burned stands were significantly more even than the logged stands, although the other diversity indices were not significantly different between treatments (table 1). Changes in the composition of the plant community resulted from changes in microclimate after forest fire or logging, particularly from higher temperatures and lower humidity (RH). These effects were most noticeable for herbaceous species, including taiga and steppe mesophytes such as *Vaccinium vitis-idaea*, *Pyrola incarnata*, and *Linnea borealis*, which were succeeded by steppe xerophytes such as *Carex duriuscula, C. lanceolata*, *Poa sibirica* and *P. attenuate*. The contribution of the taiga community (number of species) after fire decreased, from 30.6 percent in the reference stand to 11.4 percent in the burned stand and the taiga species completely disappeared after logging. For both the burned and logged stands, the characteristic forest meadow and steppe species increased relative to their proportion of the reference stand (fig. 1). The similarity coefficient of species composition between natural (reference) and burned stands was higher than that between natural and logged stands (table 2). This result indicated that logging changed species composition more drastically than burning, which is in agreement with other studies (Everett and others 1990, Rees and Juday 2002). Therefore, clearfelling has a more adverse effect on species diversity and natural regeneration than forest fire.

Changes in Microclimate

Forest fire and clearfelling altered microclimate and affected species composition and stand development (Kimmins 1997). Microclimate variables such as temperature and RH sharply changed after forest fire or logging. Temperature increased by an average of 1.6 to 1.7 °C and RH decreased up to 15.7 percent after clearfelling (fig. 2). These results suggest that environmental conditions in both the burned and the logged stands became drier than in the reference stand.

Changes in Soil Properties

Physical properties—Soil moisture significantly decreased after forest fire or clearfelling, and the extent of decrease was more severe in the logged stand (table 3). These results indicate that changes in physical soil properties such as water content and bulk density were more affected by logging than forest fire. Reduced infiltration rates lead to increased overland flow and accelerated soil erosion in Mongolia (Gombosuren 1992).

Chemical properties—The chemical properties of the soil organic layer were significantly affected by forest fire or clearfelling but not the mineral soil (table 4). Forest fire stimulated an increase in pH while significantly decreasing organic matter (OM) content. The pH increase was probably

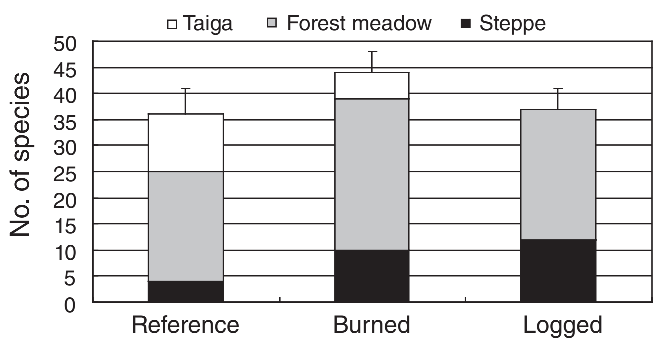


Figure 1—Changes in plant community after forest fire or logging.

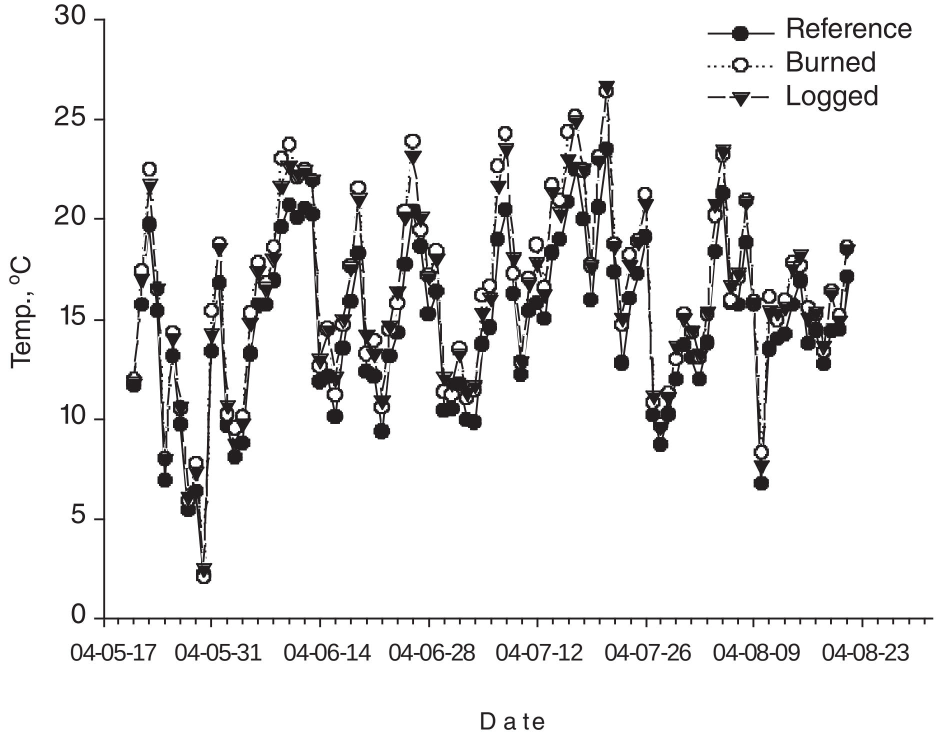
Table 1—Species diversity indices of natural, burned and logged stands

Diversity indices	Natural stand	Burned stand	Logged stand
Evenness (*J*)	0.770[b *]	0.830[a]	0.751[b]
Shannon (*H'*)	2.317	2.388	2.175
Simpson (D)	0.8467	0.8647	0.8092

* Different letter indicate significant difference at 5%

Table 2—Similarity coefficient (%) among reference, burned and logged stands

Similarity coefficient (%)	Reference-Burned	Reference-Logged	Burned-Logged
Bray and Curtis (BC)	36.8	20.9	31.3
Sørensen (Ss)	33.1	24.3	29.0



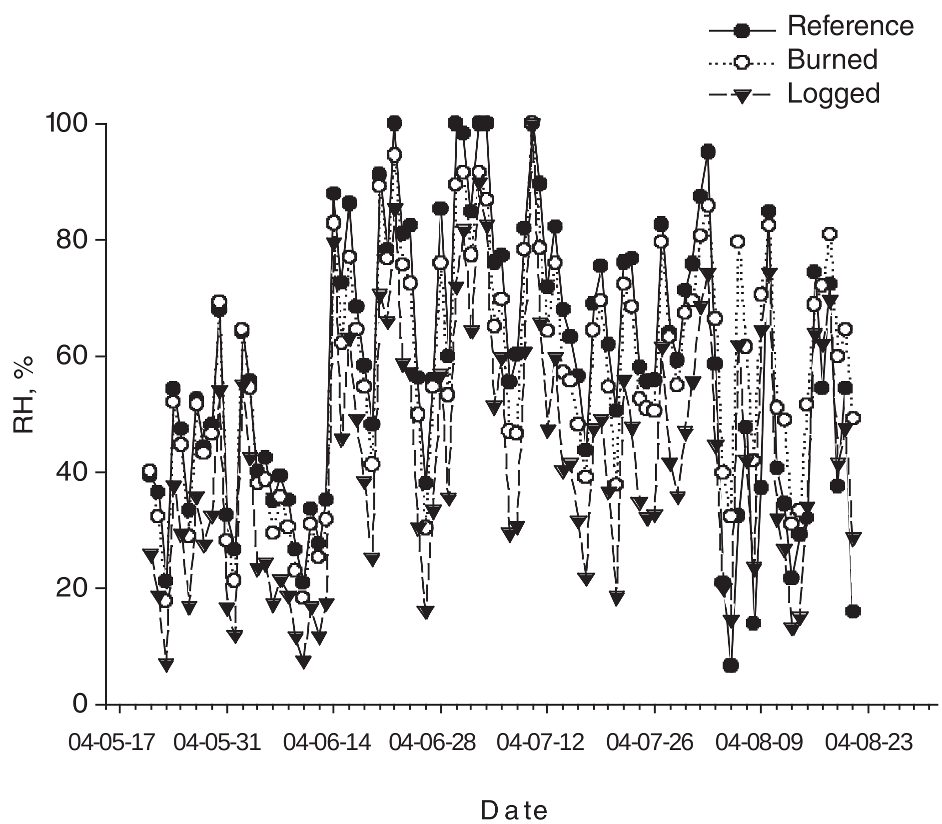


Figure 2—Daily mean temperature and RH at study sites.

Table 3—Changes in physical soil properties after forest fire or logging

Soil horizon	Study sites	Soil texture				Water content (%)	Bulk density (g cm^{-3})
		Sand (%)	Silt (%)	Clay (%)	Texture		
O	Reference	29.6 (2.7)	49.2 (2.3)	21.2 (0.5)	loam	14.3 (2.2)[a]	0.9 (0.1)
	Burned	27.5 (2.8)	46.9 (3.2)	25.6 (5.5)	loam	9.2 (1.2) [b]	0.9 (0.2)
	Logged	38.1 (4.2)	44.0 (4.5)	17.9 (0.9)	loam	6.5 (1.0) [c]	1.1 (0.1)
A	Reference	27.9 (1.4)	43.2 (3.2)	28.9 (2.9)	clay loam	13.1 (3.5) [a]	1.2 (0.1)
	Burned	20.2 (4.0)	47.3 (6.6)	32.5 (3.3)	clay loam	8.2 (0.6) [b]	1.4 (0.1)
	Logged	18.0 (2.5)	53.9 (0.6)	28.1 (3.1)	clay loam	5.9 (1.0) [c]	1.6 (0.1)
B	Reference	24.2 (5.7)	48.0 (11.7)	27.8 (7.2)	loam	5.8 (0.8) [a]	1.7 (0.1)
	Burned	18.9 (4.9)	49.5 (6.3)	31.6 (2.4)	clay loam	4.9 (0.4) [b]	1.6 (0.0)
	Logged	26.5 (1.6)	48.5 (5.7)	25.0 (5.1)	loam	3.9 (0.3) [c]	1.7 (0.0)

* Values in parenthesis indicate standard error. Different letter indicate significant difference at $p<0.05$

Table 4—Changes in pH, OM and nitrogen contents of forest soil after fire or logging

Soil horizon	Study sites	pH	OM (%)	TN (%)	Inorganic-N (mg kg^{-1})	TP (mg kg^{-1})	Available-P (mg kg^{-1})
O	Reference	5.4 (0.3) [b]	13.2 (0.9) [a]	0.71 (0.04)	5.0 (2.3) [a]	450.5	8.1 (1.3) [b]
	Burned	5.8 (0.2) [a]	9.3 (0.6) [b]	0.69 (0.16)	4.5 (2.3) [a]	532.4	37.5 (2.7) [a]
	Logged	5.4 (0.2) [b]	12.0 (0.5) [a]	0.74 (0.11)	1.1 (0.4) [b]	413.7	2.3 (0.5) [c]
A	Reference	5.4 (0.5) [b]	7.5 (0.9)	0.25 (0.08)	2.0 (0.6)	181.5	2.9 (1.5) [b]
	Burned	6.2 (0.1) [a]	6.1 (0.5)	0.23 (0.06)	0.9 (1.3)	307.7	4.5 (1.6) [a]
	Logged	5.6 (0.2) [b]	7.1 (0.2)	0.22 (0.03)	0.2 (0.0)	301.0	1.4 (0.2) [c]
B	Reference	6.0 (0.2)	4.6 (0.7)	0.09 (0.08)	0.2 (0.2)	137.9	1.3 (0.5) [b]
	Burned	6.4 (0.4)	3.7 (1.0)	0.08 (0.02)	0.1 (0.1)	176.8	2.2 (1.4) [a]
	Logged	6.1 (0.4)	4.3 (0.5)	0.04 (0.01)	0.0 (0.0)	91.7	1.2 (0.1) [b]

* Values in parenthesis indicate standard error. Different letters indicate significant difference at $p<0$

caused by ash deposition on the soil surface after fire (DeBano and others 1998, Fisher and Binkley 2000). Logging caused a significant decrease of inorganic N (NH_4^+-N, NO_3^--N) in the forest floor (O horizon) compared to the composition of the O horizon of the natural and burned stands. Available P in the mineral soil significantly increased after fire, although it decreased after logging. These results indicate that clearfelling caused more adverse changes in species composition and soil properties than were caused by forest fire. Loss of the forest floor and surface mineral soil by improper logging activity can be a serious obstacle to reforestation or rehabilitation (Giardina and Rhoades 2001) and soil and nutrient losses through erosion and leaching may lower site productivity.

CONCLUSIONS

Severe degradation led to bush and steppe stand conditions, where natural regeneration progressed slowly or did not occur for a long time. Thus, artificial regeneration (planting) is needed on these sites. Microclimate conditions such as temperature and RH drastically change after forest fire or clearfelling. The increased temperature and decreased RH mainly affected understory species composition. Forest fire and clearfelling significantly decreased soil moisture, which adversely affect seedling regeneration and growth by limiting water availability. The organic layer was more affected than mineral soil horizons. In the mineral soil, available P increased after fire and decreased after logging.

Exploitive logging and wildfires are the major causes of forest degradation in Mongolia. This research showed that logging activity more negatively affected vegetation and soil properties than fire. Thus, restoration of forest degraded by logging should have a higher priority for restoration than sites degraded by fire.

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EFFECT OF THINNING ON PARTITIONING OF ABOVEGROUND BIOMASS IN NATURALLY REGENERATED SHORTLEAF PINE (*PINUS ECHINATA* MILL.)

Charles O. Sabatia, Rodney E. Will, and Thomas B. Lynch[1]

INTRODUCTION

In traditional harvesting systems, yield of forest stands may increase if a greater proportion of net primary production is allocated to bole wood. However, for management related to whole-tree harvesting, carbon sequestration, biofuels, and wildland fire avoidance, assessments of biomass partitioning to all aboveground components is needed. Thinning increases bole growth of residual trees; it also affects the growth and partitioning of biomass to other stand components. Given the emphasis on new objectives and management strategies, it is necessary to understand how thinning and stocking density affect allocation of biomass in all the aboveground tree parts. The objectives of this study were, therefore, to quantify the biomass (in kg/ha) in aboveground tree components in shortleaf pine stands that were thinned to different stockings and compare the biomass proportions for the different aboveground tree components, i.e., bole wood, bole bark, foliage, and branch.

METHODS

The study site was located in the Ouachita Mountains in Pushmataha County in southeast OK, on industrial forest land owned by Plum Creek Timber Company. In 1990, Wittwer and others established a thinning study in dense previously unthinned naturally regenerated shortleaf pine stands. The stands were 30 to 37 years old with a basal area of 44 m^2/ha. Measured site index at base age 50 averaged 22.3 m (Wittwer and others 1998).

Nine 0.08-ha circular plots, each surrounded by a 10.1-m buffer strip, were established in the stands to serve as experimental units. These plots were assigned to two thinning treatments and an unthinned control in a randomized complete block experimental design. The two thinning treatments were 1) thinned to 70 percent of full stocking, and 2) thinned to 50 percent of full stocking. The plots assigned to the thinning treatments were thinned to the required densities using the low thinning method.

Biomass data were collected in January and February of 2006. Four trees, sampled across the diameter classes in a plot, were harvested from each of the nine experimental plots. Each felled tree was cut into logs of 2.13 m and weighed. A disc about 3-cm-hick was sampled from the upper end of each log and from the stump. Green and dry weight of wood and bark on each disk were determined. Dry weight-green weight ratios were used to estimate bole wood and bark dry weight of each sampled tree. The terminal leader and one branch randomly selected from every whorl of branches on the sample trees were harvested. Foliage was plucked from the harvested branches. Dry weights of branches and foliage on the sampled branches were determined. Regression equations based on branch basal diameter were used to estimate branch and foliage dry weights for the unsampled branches. Branch and foliage dry weight on each sample tree were obtained by summing up dry weights of individual branches on the sample trees.

Tree biomass equations, fitted by nonlinear seemingly unrelated regression, were used to estimate the dry weight of each tree component on each tree in each experimental plot. Tree level biomass estimates were summed up and converted to per hectare estimates.

The effect of the treatments was investigated by doing an analysis of variance and multiple comparisons of the treatment means by the Restricted Maximum Likelihood approach using the MIXED procedure in SAS/STAT® software, Version 9.1.3 (SAS Institute Inc. 2000-2004). The hypothesis of equality of the means was rejected at p-value ≤ 0.05 experiment-wise type I error rate.

RESULTS

Unthinned stands had more bole wood, bark, and foliage standing biomass but less branch standing biomass, per hectare, than the thinned stands. Total per hectare aboveground standing biomass was also higher in unthinned stands. However, no difference was observed in bole wood biomass and foliage biomass proportions among the three treatments. Bark biomass proportion was, however, significantly higher in unthinned controls with the proportion in the two thinning treatments being similar. The proportion in branches was significantly higher in the thinned to 50 percent treatment when compared to the proportion in the unthinned controls.

CONCLUSIONS

Thinning naturally regenerated shortleaf pine stands at the age of 30 to 37 years did not affect the proportion of biomass partitioned to stem or foliage. Thinning, however, increased partitioning of biomass to branches and decreased partitioning to bole bark. These results indicate that thinning 1) does not alter the relationship between total aboveground growth and bole wood production, 2) increases branch production which may be utilized in whole-tree harvesting systems and contribute to coarse woody fuels, and 3) does not alter the proportion of aboveground growth partitioned

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to leaf biomass, an important consideration for carbon and nutrient cycling and fine fuels.

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SECOND-YEAR GROWTH AND BOLE QUALITY RESPONSE OF RESIDUAL POLETIMBER TREES FOLLOWING THINNING IN AN EVEN-AGED BOTTOMLAND HARDWOOD SAWTIMBER STAND

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Abstract—Poletimber trees were classified as either superior or inferior poletimber stock, and then retained on separate plots receiving identical thinning treatments. Differences in post-treatment response were used to evaluate the potential of the two poletimber classes to produce grade sawtimber in the thinned sawtimber stand. Treatments included: an unthinned control, two levels of the Desirable treatment (retained preferred and desirable sawtimber and either superior or inferior poletimber), and two levels of the Acceptable treatment (retained preferred, desirable, and acceptable sawtimber and either superior or inferior poletimber). Thinning increased the likelihood that poletimber trees we initially classified as superior will yield sawlogs in the thinned sawtimber stand. Sawtimber production from inferior poletimber seems unlikely. The Desirable treatment yielded the greatest 2 year cumulative diameter growth response by superior poletimber trees (0.49 inches), but also adversely affected the bole quality of these potentially more valuable stems (10.1 new epicormics). The Acceptable treatment yielded significant diameter growth by superior poletimber trees as well (0.31 inches), and reduced epicormic branching by nearly 60 percent of that observed in the Desirable treatment during the 2-year period. Superior red oak poletimber trees in the Acceptable treatment grew at a rate equivalent to 2 inches per decade while averaging fewer than five defect-causing epicormic branches after the first 2 years. Our preliminary conclusions are that the Acceptable treatment may provide the best combination of growth and maintenance of bole quality for growing high quality sawtimber from poletimber, particularly from the potentially more valuable red oak poletimber trees.

INTRODUCTION

Poletimber trees are usually abundant in previously unmanaged even-aged, bottomland hardwood sawtimber stands. During stand development, these poletimber trees grow slower than their contemporary sawtimber neighbors and therefore, usually occupy the mid-canopy in subordinate crown positions. Most of these trees are of poor form, in declining health, and do not contain potential for development into grade sawtimber. To improve stand health and quality, these weaker poletimber trees are usually removed for pulpwood during thinning operations in these stands. Fewer scattered poletimber trees in these even-aged sawtimber stands are of good form and quality and exhibit potential sawtimber merchantability. Premature removal of these vigorous poletimber trees during thinning underutilizes this potential and could represent substantial losses in potential sawtimber revenue by the end of the rotation. Their retention, however, does not guarantee their ascendance into the sawtimber product class. Sawtimber production will hinge greatly on three factors: improvement in diameter growth, preservation or improvement of bole quality, and achievement of both within the time remaining in the rotation.

Poletimber trees selected for retention in these thinned sawtimber stands must grow and compete for site resources with much larger sawtimber neighbors. Unfortunately, residual poletimber trees are often an overlooked and underutilized component in thinned sawtimber stands, and therefore, we know very little of their post-thinning growth response potential. Several studies, however, indicated that hardwood poletimber trees have the ability to respond vigorously in diameter growth following other forms of partial cutting in bottomland stands (Johnson 1950, Johnson 1968, Meadows 1988). General findings from these earlier experiments indicated that diameter growth was highly correlated with tree health and vigor, as characterized by crown shape and size (Meadows 1988); pre-release diameter and diameter growth rates (Johnson 1968, Meadows 1988); species (Johnson 1968, Meadows 1988); and degree of release (Johnson 1950, Johnson 1968).

Unfortunately, increases in diameter, volume, and potential value may be completely offset by epicormic branching and subsequent reduction in future log grade. Most poletimber trees in these sawtimber stands are at a competitive disadvantage due to their subordinate crowns. Consequently, they are less vigorous than their sawtimber neighbors and generally are more susceptible to epicormic branching, especially when exposed to higher levels of light such as following thinning (Meadows 1995). To develop grade sawtimber from poletimber trees, we need practical guidelines to help identify vigorous poletimber trees that will not be degraded following thinning in these sawtimber stands.

A newly developed tree classification system for southern hardwoods (Meadows and Skojac 2008) separates hardwood poletimber trees into two broad classes based on several characters that may indicate their potential to produce grade sawtimber. This system could be used as a guide when selecting poletimber trees for retention following thinning in sawtimber stands. The new system expands Putnam's

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(Putnam and others 1960) set of four tree classes to five tree classes used exclusively for sawtimber (in descending order of desirability): (1) preferred growing stock, (2) desirable growing stock, (3) acceptable growing stock, (4) cutting stock, and (5) cull stock; and creates two additional classes for poletimber: (1) superior poletimber stock and (2) inferior poletimber stock. Superior poletimber stock consists of poletimber trees of a desirable or acceptable commercial species, which are of good form and quality, and currently contain the potential for a Grade 2 butt log once size requirements are met. Comparatively, inferior poletimber stock consists of poletimber trees that do not contain the potential for a Grade 2 butt log because of poor form or quality. Inferior poletimber trees should be removed during the next entry into the stand.

The classification of poletimber trees used in this new system is a qualitative assessment of their current health and condition, but actual differences in thinning response and grade sawtimber development have not been tested, nor have levels of thinning which may improve diameter growth while preserving bole quality been identified. Therefore, the objectives of this study were to (1) compare the growth and quality responses of trees within the two poletimber classes to several levels of thinning to determine their potential for sawtimber production, and (2) to identify a level of thinning which may successfully promote sawtimber production from residual poletimber trees in thinned sawtimber stands.

SITE DESCRIPTION

The experiment was conducted in an even-aged bottomland hardwood stand within the alluvial floodplain of the Red River, on Barksdale Air Force Base in southwestern Bossier Parish, in northwestern LA. The study site is part of a larger 188-acre stand that was approximately 60 to 65 years old at the time of study establishment. Prior to treatment, the stand averaged 119 trees (75 poletimber trees) and 110 square feet (30 square feet in poletimber) of basal area per acre in trees 5.5 inches and larger d.b.h. Quadratic mean d.b.h. was 13.1 inches. Average stand stocking was 92 percent (Goelz 1995). Stand basal area consisted of 47 percent red oak [cherrybark oak (*Quercus pagoda* Raf.), Nuttall oak (*Q. nuttallii* Palmer), water oak (*Q. nigra* L.), and willow oak (*Q. phellos* L.)], 38 percent sweetgum (*Liquidambar styraciflua* L.), and 15 percent other species, primarily pecan [*Carya illinoensis* (Wangenh.) K. Koch] and American elm (*Ulmus americana* L.). The study area contained nearly equal areas of both Perry clay (very-fine, smectitic, thermic Chromic Epiaquerts) and Gallion silt-loam (fine-silty, mixed, superactive, thermic Typic Hapludalfs) (USDA Soil Conservation Service 1962, USDA Natural Resources Conservation Service 2003). Site indices based on the Baker and Broadfoot (1979) site evaluation method were estimated as 104 feet for cherrybark oak, 97 feet for water and willow oak, 94 feet for Nuttall oak, and 107 feet for sweetgum.

PROCEDURE

In December of 2003, the following five treatments were applied to 2.0-acre treatment plots measuring 5 by 4 chains and replicated three times in a randomized complete block design: (1) unthinned control, (2) desirable growing stock with superior poletimber (DesSupP), (3) desirable growing stock with inferior poletimber (DesInfP), (4) acceptable growing stock with superior poletimber (AccSupP), and (5) acceptable growing stock with inferior poletimber (AccInfP). Tree classes (see footnote[2]) were used to form the cutting priority within treatments, such that each treatment was defined by the tree classes to be retained (table 1). Treatments 2 and 3 are collectively referred to as Desirable and 4 and 5 as Acceptable. Although inferior poletimber trees would generally be removed during commercial hardwood thinnings, we retained inferior poletimber trees in two of the four thinned treatments in order to compare responses between superior and inferior poletimber trees, particularly within treatments of similar overstory removal.

Prior to treatment, species, d.b.h., tree class, and crown class were recorded for every tree greater than or equal to 5.5 inches d.b.h. on 0.6 acre interior measurement plots of 3 by 2 chains. Sawtimber tree classes were assigned to trees greater than or equal to 12.5 inches d.b.h., and poletimber tree classes were assigned to trees between 5.5 and 12.4 inches d.b.h. Immediately after thinning, we recorded the number of epicormic branches on the 16-foot butt log of the residual poletimber trees. Individual epicormic branches were tallied according to their location by height (at half-foot intervals) and cardinal direction on the butt log section so that new epicormic branches could be detected in subsequent years. Individual epicormics were also classified as either non-defect (less than 3/8 inches basal diameter) or defect causing branches (greater than 3/8 inches basal diameter) (Rast and others 1973). In cases where the number of epicormic branches on the 16-foot butt log exceeded 30, only a count was taken. Diameter growth and epicormic branching were assessed annually during the two years following treatment. First year results were reported in Skojac and others (2007).

RESULTS AND DISCUSSION

Residual Stand Conditions

The intensity of removals within each of the four thinning treatments was defined by initial stand quality, expressed by the tree class distribution in the pre-thinned stand. Treatments were not intended to reduce stand density to predetermined post-harvest levels. Post-harvest stand conditions are summarized in table 2. By design, Desirable treatments were thinned more heavily than Acceptable treatments. Within both levels of sawtimber retention (i.e., Desirable and Acceptable), reduction in stand density was greater in those treatments retaining superior poletimber than in corresponding treatments retaining inferior poletimber. Therefore, thinning was heaviest in the DesSupP treatment and lightest in the AccInfP treatment. All four levels of thinning significantly reduced residual stand density relative to the unthinned control (table 2).

Residual Poletimber Characteristics

Prior to thinning, the stand contained many weak, poorly formed, or otherwise defective poletimber trees that we classified as inferior poletimber. A smaller number of poletimber trees met our criteria for the superior class. Therefore, following thinning, inferior poletimber trees were 3 to 4 times more numerous than superior poletimber trees in corresponding thinning treatments (table 3). Within the

Table 1—List of five thinning treatments, including tree classes to be retained

	Treatments				
Tree class	Control	DesSupP[a]	DesInfP	AccSupP	AccInfP
Preferred	X[b]	X	X	X	X
Desirable	X	X	X	X	X
Acceptable	X			X	X
Cut	X				
Cull	X				
Superior poletimber	X	X		X	
Inferior poletimber	X		X		X

[a]DesSupP = Desirable Growing Stock with Superior Poletimber Stock, DesInfP = Desirable Growing Stock with Inferior Poletimber Stock, AccSupP = Acceptable Growing Stock with Superior Poletimber Stock, and AccInfP = Acceptable Growing Stock with Inferior Poletimber.

[b]X indicates tree classes to be retained following application of thinning treatment.

thinned treatments, superior poletimber trees were nearly equally distributed between the red oaks and sweetgum, whereas sweetgum accounted for over 65 percent of residual inferior poletimber trees. Residual superior poletimber trees in this stand were approaching minimum sawtimber size (12.5 inches d.b.h.) and were no more than 2.6 inches below sawtimber d.b.h. at the post-harvest evaluation (table 3). In contrast, residual inferior poletimber trees were nearly 2.0 inches smaller in diameter than their superior poletimber counterparts, and averaged over 4.0 inches below minimum sawtimber d.b.h. Residual superior poletimber trees also averaged fewer than 4 epicormic branches on the butt log, a level acceptable for grade sawtimber production (table 3). In contrast, residual inferior poletimber trees in corresponding thinning treatments averaged two to three times more epicormic branches than their superior poletimber counterparts, but these differences were not statistically significant.

Table 2—Residual stand conditions immediately following application of treatments

Treatment	Trees Per Acre	Basal Area	Quadratic Mean DBH	Stocking
	number	*feet*^{2}*/acre*	*inches*	*percent*
Control	113 a[a]	117 a	13.8 b	98 a
DesSupP[b]	34 d	42 d	15.0 b	35 d
DesInfP	64 c	59 c	13.1 b	50 c
AccSupP	38 d	65 c	17.7 a	52 c
AccInfP	87 b	80 b	13.1 b	67 b

[a]Means followed by the same letter within a column are not significantly different at the 0.05 level of probability using Duncan's New Multiple Range Test.

[b]DesSupP = Desirable Growing Stock with Superior Poletimber Stock, DesInfP = Desirable Growing Stock with Inferior Poletimber Stock, AccSupP = Acceptable Growing Stock with Superior Poletimber Stock, and AccInfP = Acceptable Growing Stock with Inferior Poletimber.

Diameter Growth

Cumulative diameter growth of superior poletimber trees varied significantly following the two levels of thinning (table 4). During the 2 years following thinning, superior poletimber trees in the Desirable treatment (DesSupP) grew 58 percent more in diameter than superior poletimber trees in the Acceptable treatment (AccSupP). Both levels of thinning, however, yielded significant increases in cumulative diameter growth of the superior poletimber trees compared to the diameter growth of poletimber trees in the unthinned control. Thus far, only the superior poletimber trees in the DesSupP treatment have grown significantly more than their inferior poletimber counterparts in corresponding thinning treatments. Cumulative diameter growth of superior poletimber trees in the DesSupP treatment averaged 2 to 2.3 times the average cumulative diameter growth of inferior poletimber trees in either treatment during the first 2 years. Cumulative diameter growth of inferior poletimber trees 2 years following treatment has been uniformly low following both levels of thinning (DesInfP and AccInfP), and did not differ significantly from growth of poletimber trees in the unthinned control.

Within the superior poletimber class, average cumulative diameter growth during the first 2 years following thinning has been greatest among the red oaks (table 4). Slightly less growth was observed among superior sweetgum poletimber trees. Within the inferior poletimber class, average cumulative diameter growth of the red oaks and sweetgum

Table 3—Post-harvest attributes of residual poletimber trees, by treatment

Treatment	Trees per acre	Diameter	Epicormics
	number	*inches*	*number*
Control	68.9	8.4 b[a]	8.6 a
DesSupP[b]	10.6	9.9 a	3.0 a
DesInfP	35.6	8.1 b	7.3 a
AccSupP	10.6	10.3 a	3.6 a
AccInfP	45.9	8.4 b	10.6 a

[a]Means followed by the same letter within a column are not significantly different at the 0.05 level of probability using Duncan's New Multiple Range Test.

[b]DesSupP = Desirable Growing Stock with Superior Poletimber Stock, DesInfP = Desirable Growing Stock with Inferior Poletimber Stock, AccSupP = Acceptable Growing Stock with Superior Poletimber Stock, and AccInfP = Acceptable Growing Stock with Inferior Poletimber.

was similar 2 years following both the Desirable and Acceptable treatments. Because we observed wide variation in cumulative diameter growth response within individual species groups, differences within species groups were not significant across the five levels of thinning after the second year (table 4).

Though preliminary, it appears that we have been successful in identifying poletimber trees capable of rapid diameter growth response following thinning. Thinning increased diameter growth of superior poletimber trees by 138 to 277 percent compared to growth of poletimber trees in the unthinned control. Thinning did not significantly improve the growth of inferior poletimber trees in the 2 years following treatment. The largest increases in diameter have been observed among the superior red oak poletimber trees (0.48 and 0.40 inches in the DesSupP and AccSupP treatments, respectively). If these growth rates can be maintained, it is conceivable that the superior red oak poletimber trees will yield small sawlogs within a decade after thinning in this sawtimber stand. A slightly longer period of time may be required for superior sweetgum poletimber trees to yield sawtimber products.

Table 4—Average 2-year cumulative diameter growth of all residual poletimber trees, residual red oak poletimber trees, and residual sweetgum poletimber trees, by treatment

	2-Year Cumulative Diameter Growth		
Treatment	All Trees	Red oaks	Sweetgum
	---------------------*inches*---------------------		
Control	0.13 c[a]	0.19 a	0.14 a
DesSupP[b]	0.49 a	0.48 a	0.41 a
DesInfP	0.25 bc	0.36 a	0.31 a
AccSupP	0.31 b	0.40 a	0.28 a
AccInfP	0.21 bc	0.23 a	0.27 a

[a]Means followed by the same letter within a column are not significantly different at the 0.05 level of probability using Duncan's New Multiple Range Test.

[b]DesSupP = Desirable Growing Stock with Superior Poletimber Stock, DesInfP = Desirable Growing Stock with Inferior Poletimber Stock, AccSupP = Acceptable Growing Stock with Superior Poletimber Stock, and AccInfP = Acceptable Growing Stock with Inferior Poletimber.

Epicormic Branching

The production of new epicormic branches on the 16 foot butt log of superior poletimber trees in the DesSupP treatment increased during the second year, exceeding the rate observed during the first year by nearly two branches (table 5). Production of new epicormic branches remained consistent from year 1 to year 2 across the other treatments, and was roughly 1/3 the rate observed in the DesSupP treatment during the second year. As a result, the cumulative number of new epicormic branches (i.e., new branches in year 1 and year 2 less mortality of new branches from year 1) produced by superior poletimber trees in the DesSupP treatment was significantly greater than the cumulative number of new epicormic branches produced by poletimber trees in the other four treatments (table 5). Two years following treatment, superior poletimber trees in the DesSupP treatment averaged four times as many new epicormic branches as poletimber trees in the unthinned control, and two to nearly four times as many new epicormic branches as inferior poletimber trees in either treatment. It is important to note that superior poletimber trees in the AccSupP treatment averaged 57 percent fewer new epicormic branches than superior poletimber trees in the DesSupP treatment at the end of the second year.

The total number of epicormic branches increased four-fold on superior poletimber trees in the DesSupP treatment during the 2 years following thinning (table 6). In contrast, superior poletimber trees in the AccSupP treatment averaged a net increase of less than three total epicormic branches (less than a two-fold increase) during the same time period. Inferior poletimber trees experienced a moderate net increase in total epicormic branches during the first 2 years, but still contain too many branches for high quality sawtimber production. Poletimber trees in the unthinned control averaged a slight net decrease in total epicormic branches during the 2-year period.

Red oak poletimber trees have been most affected by the production of epicormic branches during the 2 years since thinning. For example, 86 percent, or approximately 11 of the nearly 13 epicormic branches on superior red oak poletimber trees in the DesSupP treatment were large enough to cause defects on a small sawlog (fig. 1). Large, defect-causing epicormic branches on inferior red oak poletimber trees were also prominent, averaging nearly 13 and over 7.5 branches in the DesInfP and AccInfP treatments, respectively. It should be noted that superior red oak poletimber trees in the AccSupP treatment averaged less than five defect-causing epicormic branches 2 years following thinning. In general,

Table 5—Average number of new epicormic branches produced during Year 1 and Year 2, and the cumulative number of new epicormic branches produced by residual poletimber trees, by treatment

	New Epicormic Branches		
Treatment	Year 1	Year 2	Net-Cumulative
	--------------------*number*--------------------		
Control	1.2 c[a]	1.5 b	2.5 b
DesSupP[b]	4.3 a	6.0 a	10.1 a
DesInfP	3.1 ab	2.4 b	5.0 b
AccSupP	2.2 bc	2.2 b	4.3 b
AccInfP	1.4 c	1.5 b	2.8 b

[a]Means followed by the same letter within a column are not significantly different at the 0.05 level of probability using Duncan's New Multiple Range Test.

[b]DesSupP = Desirable Growing Stock with Superior Poletimber Stock, DesInfP = Desirable Growing Stock with Inferior Poletimber Stock, AccSupP = Acceptable Growing Stock with Superior Poletimber Stock, and AccInfP = Acceptable Growing Stock with Inferior Poletimber.

sweetgum poletimber trees have been less susceptible to epicormic branching during the 2 years following thinning (fig. 1). Epicormic branches on sweetgum poletimber trees were also smaller than those on the red oaks. In fact, sweetgum poletimber trees averaged no more than four defect-causing epicormic branches across the five levels of thinning after the second year.

Table 6—Average total number of epicormic branches, immediately post-harvest and at Year 2, on residual poletimber trees, by treatment

	Total Epicormic Branches	
Treatment	Post-harvest	Year 2
	----------------- *number* ------------------	
Control	8.9 a[a]	8.6 a
DesSupP[b]	3.1 a	12.2 a
DesInfP	6.7 a	10.1 a
AccSupP	3.7 a	6.5 a
AccInfP	10.4 a	12.1 a

[a]Means followed by the same letter within a column are not significantly different at the 0.05 level of probability using Duncan's New Multiple Range Test.

[b]DesSupP = Desirable Growing Stock with Superior Poletimber Stock, DesInfP = Desirable Growing Stock with Inferior Poletimber Stock, AccSupP = Acceptable Growing Stock with Superior Poletimber Stock, and AccInfP = Acceptable Growing Stock with Inferior Poletimber.

It is clear that thinning adversely affected the bole quality of superior poletimber trees in the DesSupP treatment, particularly superior red oak poletimber trees (see fig. 1). The DesSupP treatment was the most severe of the thinning treatments applied, removing nearly 2/3 of the preharvest basal area. These severely reduced residual conditions spawned significantly higher levels of epicormic branching on the superior poletimber trees in this treatment. Net cumulative production of new epicormic branches within the DesSupP treatment was over twice that observed by superior poletimber trees in the AccSupP treatment over the 2 year period studied. Nearly 90 percent of the epicormic branches on superior red oak poletimber trees in the DesSupP would cause defects on a small log. The more moderately thinned AccSupP treatment appeared to minimize the production of epicormic branches on the potentially more valuable superior red oak poletimber trees. Defect-causing epicormic branches on superior red oak poletimber trees in this treatment were below levels believed capable of causing a reduction in log grade on red oak sawtimber trees (Meadows and Burkhardt 2001). Though preliminary, retention of the acceptable growing stock sawtimber class, as specified by the marking rules for the AccSupP treatment, seemed to create residual stand conditions more favorable for protecting the boles of the superior poletimber trees.

CONCLUSIONS

Thinning increased the likelihood that the poletimber trees we initially classified as superior will yield quality sawlogs in

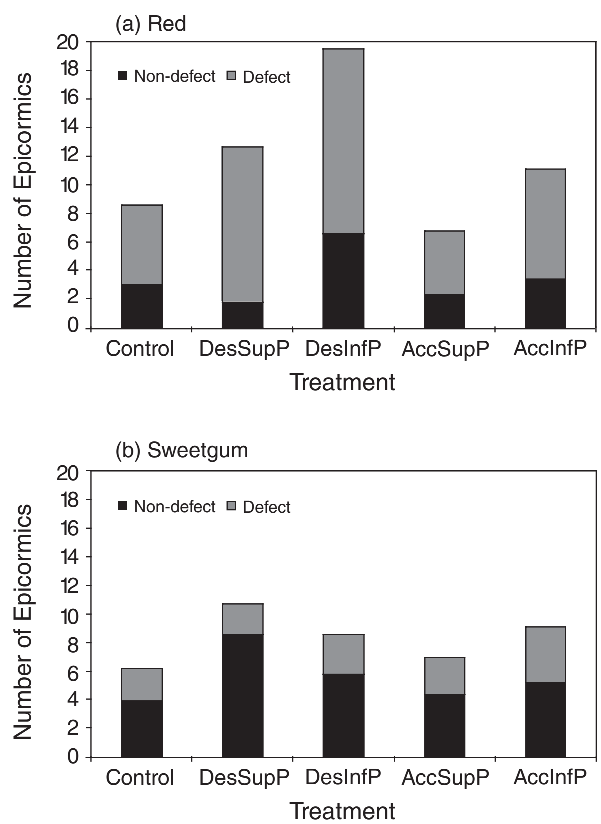

Figure 1—Average number of non-defect and defect causing epicormic branches on residual (a) red oak and (b) sweetgum poletimber trees 2 years following thinning, by treatment.

the thinned sawtimber stand. Quality sawtimber production from their inferior poletimber counterparts seems unlikely. The DesSupP treatment yielded the greatest diameter growth response of the superior poletimber trees, but also adversely affected the bole quality of these potentially more valuable stems. The AccSupP treatment yielded significant diameter growth by superior poletimber trees as well, and reduced epicormic branching by nearly 60 percent of that observed in the DesSupP treatment during the 2-year period. Superior red oak poletimber trees in the AccSupP treatment grew at a rate equivalent to 2 inches per decade while averaging fewer than five defect-causing epicormic branches after the first 2 years. Based on these preliminary results, it appears that the AccSupP treatment may provide the best combination of diameter growth and maintenance of bole quality for growing quality sawlogs from residual superior poletimber trees in thinned sawtimber stands, particularly from the potentially more valuable red oaks.

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WOOD QUALITY FOR LONGLEAF PINES: A SPACING, THINNING AND PRUNING STUDY ON THE KISATCHIE NATIONAL FOREST

Chi-Leung So, Thomas L. Eberhardt, Daniel J. Leduc, Leslie H. Groom, and Jeffrey C.G. Goelz[1]

Abstract—Twenty 70-year-old longleaf pine (*Pinus palustris* Mill.) trees were harvested from a spacing, thinning, and pruning study on the Kisatchie National Forest, LA. Tree property mapping was used to show the property variation within and between three of the trees. The construction of such maps is both time consuming and cost prohibitive using traditional test methods. However, we were able to construct tree property maps using NIRVANA (Near InfraRed Visual and Automated Numerical Analysis), a spectroscopic system developed for automated property determination for increment cores. This allows wood quality to be determined throughout the tree, and presented in the form of a readily interpretable map. Thus, the effects of spacing, thinning and pruning at different ages were observed within, as well as, between trees. The effect of high levels of extractives in the heartwood on the property determinations remains to be completely resolved.

MATERIALS AND METHODS

Trees were harvested and 2-inch disks cut approximately every 2 feet along the bole. The disks were then further sectioned into 0.5-inch wood slices, from bark to bark and through the pith in the north-south direction. The slices were scanned using NIRVANA as previously described elsewhere (So and others 2006) with specific gravity values predicted along each slice. The model used for predicting specific gravity was based on data collected from a previous longleaf study (So and others 2006). Following early results, several slices then underwent extraction with acetone followed by further scanning for comparative purposes.

RESULTS AND DISCUSSION

Tree property maps generally show a large variation in properties within a tree (So and others 2002). The results presented were for three trees with varying spacing and thinning regimes. It was shown for the fast-grown tree that there was a high level of extractives in the heartwood nearer the base of the tree. This resulted in very high specific gravity values in this region. Generally, specific gravity decreased with height. The trees with smaller d.b.h., and correspondingly slower growth, showed few regions of very low specific gravity as one would expect. The sensitivity of this technique, and particularly the presence of extractives, plays a major role in determining the resultant pattern. After scanning, some of the samples underwent extraction and were then scanned again. The specific gravity values on the extractive-free wood were much lower in the heartwood than previously observed, indicating both extractives removal and the presence of juvenile wood. Maps can be easily generated for other properties such as stiffness and strength. The data from NIRVANA can be meshed with the collection of growth and yield data.

CONCLUSIONS

NIRVANA can be used for property mapping of trees in a timely manner. Thus, it is possible to show the effects of silvicultural treatments throughout a tree, thereby allowing treatment comparisons. It is anticipated that the property variation within trees can be explained by their treatment and growing history.

ACKNOWLEDGMENTS

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HARDWOOD REGENERATION RELATED TO OVERSTORY SHORTLEAF PINE (*PINUS ECHINATA* MILL.) BASAL AREA, SITE INDEX, AND TIME SINCE CUTTING IN ARKANSAS AND EASTERN OKLAHOMA

Douglas J. Stevenson, Thomas B. Lynch, and James M. Guldin[1]

INTRODUCTION

Shortleaf pine grows in association with many other species, particularly understory hardwoods, which compete with it, limiting its productivity (Bower and Ferguson 1968, Cain 1988). Which species are the most competitive varies with site quality, density of the pine overstory and years since thinning. Basal area and site index closely approximate the principle ordination axes, indicating their importance as proxies of competition and site quality. The objective was to measure temporal changes in species composition of the understory over a range of overstory site indices, stand ages and stocking levels.

METHODS

Over 200 fixed-radius 0.081-ha plots were permanently established in naturally-occurring shortleaf pine stands located in the Ozark and Ouachita National Forests during the period 1985-1987 as part of a forest growth study. The study used a 3 by 4 by 5 factorial design with three 50-year-basis site index classes (<55, 55-75 and >75), four initial age classes (11-30, 31-50, 51-70 and 71-90) and five overstory basal area classes (16-45, 45-75, 75-90, 90-135 and >135 square feet). Initially, plots were thinned to assigned basal area levels and hardwoods were treated with chemical herbicide. During the 1995-1997 re-measurement of these plots, two 0.02-ha subplots were established within each of the shortleaf growth plots to assess shortleaf regeneration and abundance of understory hardwoods. During the 2000-2001 re-measurement, an additional two 0.02-ha subplots were added. Seedling counts from each of the four subplots were added together for analysis. Fifty-two hardwood species were included.

Site index was calculated using Graney's (1976) model for each of four shortleaf pines in each plot. The results were then averaged to obtain a plot site index. For analysis, overstory basal area, site index and overstory age were treated as continuous variables.

RESULTS

Canonical correspondence analysis using CANOCO (ter Braak and Smilauer 1998) showed the overstory pine basal area, site index and time axes meeting almost at right angles, indicating low covariance among the variables and their usefulness as predictors of seedling stocking. Sweetgum (*Liquidamber styraciflua* L.) predominated on sites with pine site indices greater than 85; dogwood (*Cornus* spp. L.) on sites between 70 and 85 and red maple (*Acer rubrum* L.) on sites with pine site indices less than 70.

Sweetgum stem counts decreased exponentially as pine basal area increased. On sites with pine site indices greater than 65, seedling stem counts for sweetgum increased exponentially as site index increased, but remained constant with time (10 to 16 years after thinning).

As pine site indices increased, dogwood stem counts increased to a high at 85 square feet, and then decreased. Dogwood stem counts at first decreased with overstory pine basal area to a low at 30 square feet, and then increased exponentially with increasing basal area. Dogwood stem counts decreased for the first 12 years after thinning, then increased. After the twelfth year, there were no dogwood seedlings at all on sites with pine basal areas between 20 and 45.

Red maple stem counts decreased to a minimum at 45 square feet of overstory basal area, and then increased exponentially as overstory basal area increased. Red maple stem counts increased in a straight line as pine site index increased. Red maple reached a maximum stem count in the 11th year following thinning.

Mockernut hickory (*Carya tomentosa* Nutt.) was present on every plot. Stem counts reached a maximum at a pine site index of 60, decreasing in both directions. Stem counts reached a minimum in the 11th year following thinning, and then started to rise.

CONCLUSIONS

Sweetgum's sensitivity to pine site quality and relative insensitivity to time suggests it could be used as an indicator species for shortleaf pine site index. Sweetgum appears to suppress pine regeneration on sites with indices above 85. Red maple stem counts exceeding those of dogwood and sweetgum are indicative of pine site index below 70. Basal area of the pine overstory and pine site index are important indicators of species composition. Complex requirements of most understory species will require many different models to make prediction of species composition possible. It is theoretically possible to use species composition as a variable in predicting shortleaf pine growth and yield.

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THE EFFECTS OF TREE SHELTERS ON SEEDLING SURVIVAL AND GROWTH OF TWO BOTTOMLAND HARDWOOD SPECIES: THIRD-YEAR RESULTS

H. Christoph Stuhlinger, Jeffrey A. Earl, and Rebecca A. Montgomery[1]

Abstract—Tree shelters can aid hardwood seedling establishment by increasing early survival and growth. Tree shelters are translucent plastic tubes that act as mini-greenhouses by maintaining higher humidity environments around the seedlings (Minter and others 1992). Shelters can also protect seedlings from herbivory (Schweitzer and others 1999). Lower cost shelters may provide the same benefits as more expensive shelters.

This study was established in February 2004 at two 2.5-acre University of Arkansas research station sites in southwest and east central AR (Hope in Hempstead County and Pine Tree in St. Francis County). The purpose was to compare three types of tree shelters installed on green ash (*Fraxinus pennsylvanica* Marsh.) and cherrybark oak (*Quercus pagoda* Raf.) seedlings. The Hope site is a former hay field on a silty clay loam, and was disked twice before planting. The Pine Tree site is a former crop field on silt loam soils, and was ripped (subsoiled) before planting. The study is a replicated randomized complete block design.

Tree seedlings enclosed in 4-foot tall BLUE-X®, Protex® or Tubex® tree shelters (12 by 12 foot spacing) were observed monthly during the growing season and compared to unsheltered controls with respect to survival and height growth. Total height and groundline diameter of each seedling were measured at the end of each growing season. The BLUE-X® shelter (blue) consists of a flat Poly film and sleeve which must be assembled. The Protex® shelter (blue) is shipped flat, and must be rolled into a cylinder and secured with eight tabs. The Tubex® shelter (green) is shipped as a tube ready to install. Each shelter was held upright with a 4-foot bamboo stake. Netting was installed on the top of each tube to prevent birds from falling in.

The total establishment cost (per shelter) for each tree shelter type includes all materials and labor for assembly and installation. The BLUE-X® cost in 2004 was $1.26 per shelter, the Protex® cost was $2.36 per shelter, and the Tubex® cost was $2.64 per shelter.

After three growing seasons, tree shelters did not significantly affect seedling survival. Survival at Pine Tree was 99 to 100 percent for all four treatments for ash, and 93 to 98 percent for oak. At Hope, green ash survival was 96 to 99 percent, but cherrybark oak survival was only 74 to 84 percent. Oak survival at Hope was less than at Pine Tree, probably due to heavier soils at Hope. Deer browsed more of the unsheltered green ash than cherrybark oak control seedlings, which caused stunted growth, but not mortality. About 63 to 75 percent of the green ash control seedlings were browsed by deer at both sites. Fewer cherrybark oak controls (15 to 25 percent) were browsed.

Third-year groundline diameters at Hope were slightly greater for seedlings growing in shelters compared to controls, except oaks in BLUE-X® shelters had a slightly smaller diameter than controls. Diameters for both species at Hope ranged from 0.4 to 0.6 inches. At Pine Tree, control seedlings generally had greater diameters than sheltered seedlings. Diameters at Pine Tree ranged from 0.7 to 0.9 inches for green ash, and from 0.8 to 1.0 inches for oak. At both sites, tree shelters significantly increased height growth over the unsheltered seedlings for both species, but the differences among shelter types were negligible. At Hope, sheltered green ash heights averaged about 4 feet, and about 2.5 feet for control seedlings. Cherrybark oak heights averaged about 5 feet in shelters, and about 3 feet for controls. At Pine Tree, sheltered green ash heights were about 5.5 feet, compared to 4.5 feet for control seedlings. Cherrybark oak heights ranged from 5.5 to 6 feet in shelters, and were about 5 feet for control seedlings. Height growth of sheltered seedlings, especially at Pine Tree, was rapid the first year until the seedlings reached the tops of their shelters, after which height growth slowed down and diameter growth resumed.

Emergence was recorded when the terminal bud of each seedling reached the top of its shelter (3.9 feet, because tubes are in the ground 1 to 2 inches) or the equivalent height for controls. At Pine Tree, 96 percent of all the sheltered seedlings had emerged by the end of the third growing season, compared to 73 percent of the controls. At Hope, only 62 percent of the sheltered seedlings had emerged, compared to only 11 percent of the controls. Percentage of seedlings emerged varied the most by shelter type for green ash at Hope (50 to 68 percent), but otherwise shelter type made little difference on percentage emerged. Emergence rates (feet per month growth to reach top of shelter) at both sites were significantly greater (usually more than double) for sheltered seedlings of both species over controls. BLUE-X® and Tubex® shelters at Pine Tree produced mean growth rates of about 0.5 foot per month. Protex® growth rates were slightly less. Most (60 to 80 percent) of the sheltered seedlings at Pine Tree emerged during the first growing season (2004), whereas most emergence at Hope occurred during the second and third growing seasons.

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In general, tree shelters did not affect overall survival compared to unsheltered seedlings, and survival by shelter type varied very little. Many unsheltered controls were browsed by deer, resulting in reduced height growth. Tree shelters increased growth rates of green ash and cherrybark oak seedlings. Cherrybark oak seedlings grew slightly faster than green ash seedlings. Height growth was more pronounced than diameter growth until emergence. BLUE-X® shelters cost half as much as Tubex® shelters, but improve growth rates similarly. This study will be monitored through five growing seasons.

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EFFECTS OF HARVESTING TREATMENTS ON THE ANT COMMUNITY IN A MISSISSIPPI RIVER BOTTOMLAND HARDWOOD FOREST IN WEST-CENTRAL MISSISSIPPI

Lynne C. Thompson, David M. General, and Brian Roy Lockhart[1]

Abstract—We assessed effects that harvesting treatments had on the ant community in a Mississippi River bottomland hardwood forest in west-central MS. Ants were collected on Pittman Island using pitfall traps from July to November in 1996, 1997, and 2000. The forest received three replicated harvesting treatments in 1995, including: 1) uncut controls (check), 2) selection treatments removing 50 percent of trees, and 3) clearcut treatments. The ant community was also affected by environmental extremes, including flooding and drought. A total of six subfamilies, 20 genera, 33 species, and 19,269 individuals were collected. Cluster analysis revealed little difference in ant community diversity between check and selection treatments, but clearcuts were very different. A multi-response permutation procedure and indicator species analysis of 18 species that dominated the site, showed these species were influenced differently by the treatments. No species preferred undisturbed sites exclusively, but three showed strong preferences. Eight species did equally well in all treatments, six "liked" selection harvests almost as well as checks, and one preferred selection harvests. Red imported fire ants, *Solenopsis invicta*, increased substantially with time in all treatments.

INTRODUCTION

Ant studies have been used to understand environmental changes brought about by human activities (Ambrecht and others 2005, Andersen 1990, Andersen and Sparling 1997, Corley and others 2006, Majer and Beeston 1996, Perfecto and Vandermeer 2002). For example, ant communities have been used to assess the success of mine restoration (Andersen 1997), the effects of introduced pine on the Patagonian steppes (Corley and others 2006), and recovery in tropical forest land conversion (Dunn 2004a). More specifically, the effects of harvesting on ants have been assessed in the United States with mixed effects (Jennings and others 1986, Palladini and others 2007, Stephens and Wagner 2006, Yi and Moldenke 2005, Zettler and others 2004). Thus, we hoped a survey of ants in a bottomland hardwood forest regeneration experiment might tell us something about how clearcut and selection harvesting affects the ant community.

METHODS

Site

Ants were collected in a bottomland hardwood forest at Pittman Island, MS (fig. 1) (32° 55' N latitude, 91° 08' W longitude) receiving several harvesting treatments in 1995. The island is located within the levee system of the Mississippi River and has typical ridge/swale topography with riverfront hardwood species associations. Year 1996 was the first growing season following harvest, and included a partial flood that did not cover the ridges. In 1997, there was a one month spring flood that covered the entire island with several meters of river water. In 2000, there was an extended fall drought that lasted into December. So, in addition to the effects of treatments, we also have the yearly effects of extreme weather confounding the adjustment of ant species to the harvesting disturbance. The forests were dominated by sugarberry (*Celtis laevigata*) before treatment and this species was also favored in the selection harvest.

Harvesting Treatments

Check is undisturbed forest; selection is the removal of about 50 percent of trees, leaving the most desirable commercial species to grow, with felled noncommercial trees and tops left on site; clearcut is harvesting of all trees, with felled noncommercial trees and tops left on site (fig. 2). Each treatment and control stand was about 20 ha in size, and the three treatments were replicated three times (nine total stands) in a randomized design (fig. 1).

Ant Collecting and Species Occurrence Calculation

Ants were collected using 20 pitfall traps per stand, with the traps spaced at 10-m intervals along a transect bisecting each stand and running along the ridge. Traps were serviced weekly from July to early November in 1996, 1997, and 2000. Because we were not interested in trap effects, all ants from each stand and week were pooled. Thus, quantitative data is the occurrence of a species within treated stands by weeks and years. For example, *Solenopsis invicta* was collected in 1996 in selection stand one in only nine of the 19 total weeks, so occurrence here is nine. The number of individuals collected was not used because traps placed close to colonies of some species typically collected hundreds of individuals (for example, *S. invicta*). Total occurrence for one species depends upon trapping weeks by year. Maximum occurrence is 19 trapping weeks for 1996 and 1997 and 23 weeks for 2000. Thus, for the nine stands, the maximum occurrence over all nine stands for 1996 and 1997 is 19 weeks x nine stands = 171, and for 2000, this number is 23 weeks x nine stands = 207. Likewise, maximum occurrence by treatment for one species is calculated as total occurrence over all three years (549) divided by three treatments (183).

Data Analysis

Species diversity measures were calculated using EstimateS (Colwell 2005), including: number of observed species, singletons (number of species where only specimen was

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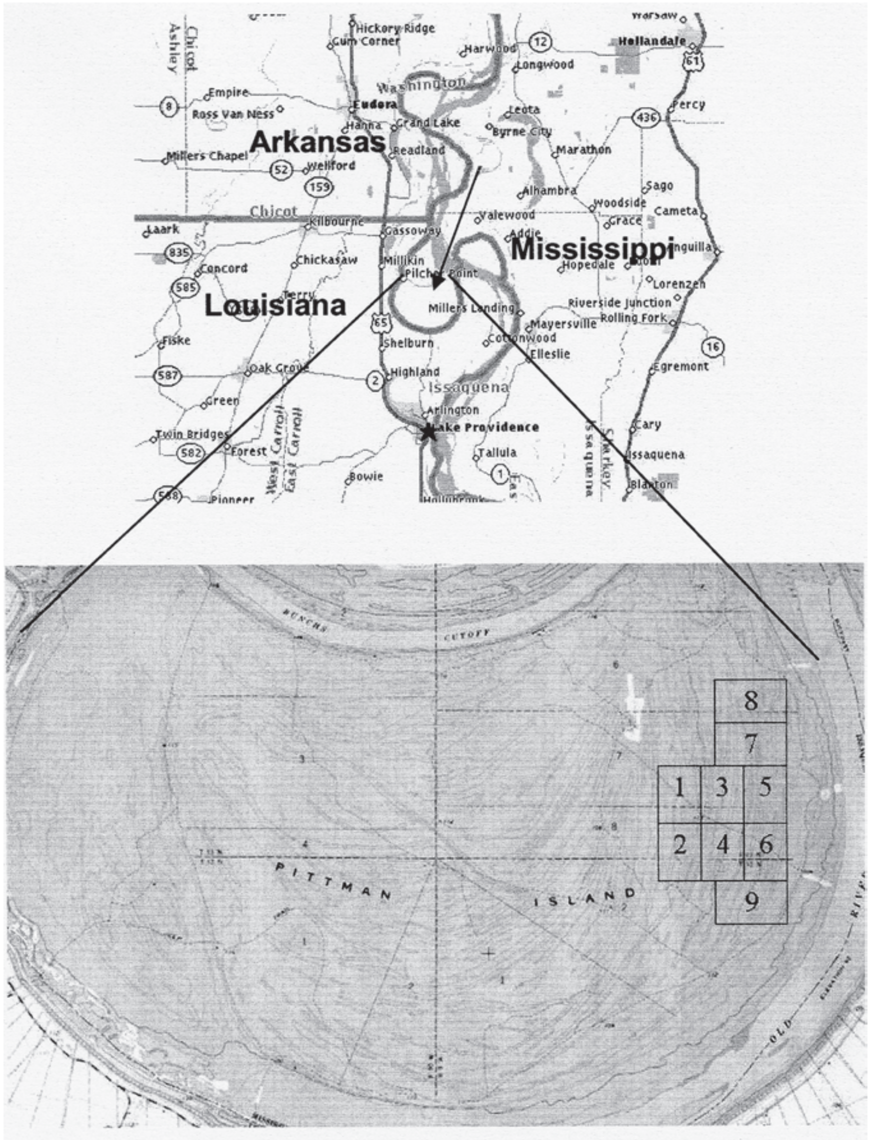

Figure 1—Location of Pittman Island (arrow), Mississippi, near the northeastern corner of Louisiana, and showing treatment layout with stands 1, 6, and 7 clearcut, 4, 5, and 8 selection, and 2, 3, and 9 control (check).

collected), doubletons (number of species where only two specimens were collected), and three richness estimators (Chao 2, Jack 2, and Bootstrap [Colwell 2005]) that, because of likely under-sampling by us, provide estimates of expected richness calculated from our data set. For more detail on these estimators see Colwell (2005).

To discover treatment effects, all stand replicates and years were pooled within treatments, then analyzed. All 33 species were included to assist interpretation. To assess the effects of treatments on the ant community, species presence/absence data and species occurrence data were both analyzed with the 2-way cluster analysis procedure in PC-ORD (McCune and Mefford 1999) using the flexible-beta linking method (beta = -0.25), and the Sorensen (Bray-Curtis) distance measure of the cluster routine, as recommended in McCune and Grace (2002). The presence/absence data were analyzed without transformation. However, for the occurrence data, treatments (rows) were first relativized using the maximum occurrence of the most abundant species in the treatment (that is, occurrence was transformed to a range of zero to one over each treatment, where one is maximum occurrence and zero is not collected), thus standardizing all treatments to the same starting point. The second clustering (columns) used the relativized totals for each species over all three treatments. The resulting image provides a two-dimensional picture of the combined relationships. To discover the yearly effects on treatments, only replicates of occurrence data were pooled, then relativized as described above, and analyzed. Because of the potential negative effects that rare species might have, only the 18 most common species were used. Rare species, those occurring in fewer than five percent of samples (McCune and Grace 2002) (in our case seven or fewer occurrences) were removed.

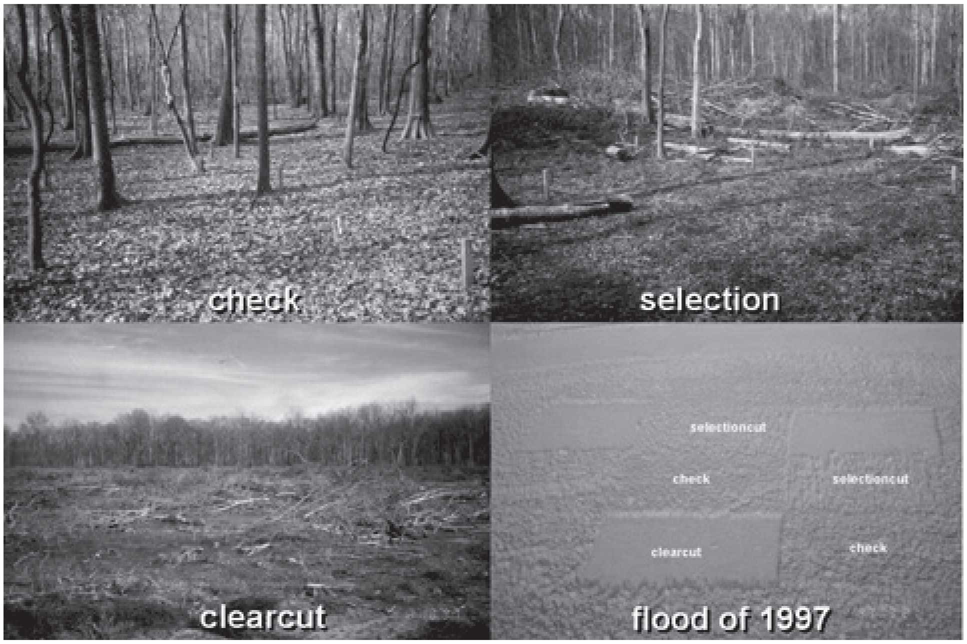

Figure 2—Images of treatments in winter of 1996 and flooding in 1997 at the Pittman Island, Mississippi, study site.

The occurrence data did not fit parametric statistics (transformations could not satisfy requirements), so non-parametrics were used (Clark 1993). The influence of treatments on the 18 most common species was analyzed by the multi-response permutation procedure (MRPP) in PC-ORD using occurrence by replicated treatment and year. Before analysis, the data set was relativized, as described above, for the treatments (rows) using the maximum occurrence of the most abundant species in the treatment stand. To tease out treatment effects, the analysis first compared all three treatments. If there were significant differences among any two, then multiple pairwise comparisons were done using a P = 0.05 significance level. The MRPP analysis used the Euclidean distance measure and Mielke group weighting (PC-ORD) to accommodate for the absence of ants in some treatment stands.

Indicator species analysis (PC-ORD) was used (by means of the procedure in Dufrene and Legendre 1997) to test faithfulness of ant species occurrence within treatments. A perfect indicator species would always be present in one treatment and never occur in other treatments; it would have a value of 100. As in the MRPP analysis, the data set was relativized within treatment stands using maximum occurrence of the most abundant species, thus standardizing all treatment stands to the same starting point. Significance was tested using a Monte Carlo method with 3,000 permutations and a significance level of P = 0.05.

RESULTS

Ants Found

Six subfamilies, 20 genera, 33 species and 19,268 individuals were collected. The occurrence of ant species by year and by treatment is shown in table 1. Of importance from this list is the absence of *Monomorium minimum*, and the single collection of *S. molesta*, both very common small ground-nesting species in AR, LA, and MS (Dash 2004, MacGowan and Hill 2007, Warren and Rouse 1969).

Ant Diversity

The number of observed species [species richness] (table 2) is lower in clearcuts over all years, and more similar in selection and check treatments. Year 1996 is very different because five species (*Camponotus pylartes, Dorymyrmex bureni, Brachymyrmex depilis, Stenamma meridionale*, and *Temnothorax curvispinosus*) disappeared in subsequent years. Other rare species (showing up only in single years) were *Cam. chromaiodes, Crematogaster missuriensis, Neivamyrmex opacithorax,* and *Trachymyrmex septentrionalis.* A measure of rare species is the number of singletons and doubletons (table 2), with singletons being much higher than doubletons within treatments in 1996 and 1997, and then reversing in 2000. The three richness estimators in table 2 show that the check treatments projected more species in 1997 and 2000.

The relationship between the ant community and treatments is shown in figure 3 (rows). The choice of data influenced the clustering results. When presence/absence data are used, the clearcuts and selections clustered together, but when occurrence data are used, the selections and checks clustered together. Although species richness data are useful, they do not provide enough information on the relative importance of each species in the community. Thus, because we have excellent occurrence data, we believe it provides a more reasonable picture of the treatment effects on our ant community. In this case, the clearcuts obviously affected the community and the selections had no effects.

The effects of treatments on individual species are shown in figure 3 (columns). When using presence/absence data

Table 1—Pittman Island, Mississippi, ant occurrence by year and treatment

SUBFAMILY/*Species*	1996	1997	2000	Clearcut	Selection	Check
ECITONINAE						
Neivamyrmex opacithorax (Emery)	0	0	2	0	0	2
DOLICHODERINAE						
Dorymyrmex bureni Trager	1	0	0	1	0	0
Tapinoma sessile (Say)	107	43	47	41	79	77
FORMICINAE						
Brachymyrmex depilis Emery	4	0	0	0	4	0
Camponotus americanus Mayr	6	4	11	3	3	15
C. castaneus (Latreille)	2	1	2	1	2	2
C. chromaiodes Bolton	0	0	1	0	1	0
C. decipiens Emery	35	17	0	2	25	25
C. discolor (Buckley)	1	0	3	0	1	3
C. pennsylvanicus (DeGeer)	101	85	32	37	84	96
C. pylartes Wheeler	1	0	0	0	0	1
Lasius alienus (Foerster)	124	65	26	53	77	85
Paratrechina terricola (Buckley)	2	1	91	52	35	7
Prenolepsis imparis (Say)	6	0	10	4	8	4
MYRMICINAE						
Aphaenogaster fulva Roger	2	10	2	2	6	6
A. tennesseensis (Mayr)	0	0	10	8	2	0
A. texana Wheeler	43	32	110	20	74	91
Crematogaster ashmeadi Mayr	21	21	17	4	31	24
C. lineolata (Say)	24	9	12	3	36	6
C. minutissima Mayr	26	8	7	0	26	15
C. missuriensis Emery	0	1	0	0	1	0
Myrmecina americana Emery	0	1	2	0	1	2
Myrmica spatulata M.R. Smith	141	87	72	41	95	163
Pheidole dentata Mayr	151	82	104	66	131	140
Solenopsis invicta Buren	67	97	142	160	108	38
S. molesta (Say)	1	1	0	0	1	1
Stenamma cf. meridionale	1	0	0	0	1	0
Temnothorax curvispinosus Mayr	1	0	0	0	0	1
Trachymyrmex septentrionalis McCook	0	0	1	0	0	1
PONERINAE						
Hypoponera opacior (Forel)	7	11	10	16	9	3
Ponera pennsylvanica Buckley	4	0	4	3	4	1
PSEUDOMYRMECINAE						
Pseudomyrmex pallidus (Fr. Smith)	3	1	0	0	0	4
TOTALS	**881**	**577**	**717**	**517**	**845**	**813**
Number of species	**26**	**20**	**23**	**19**	**26**	**27**

the rare species typically cluster together because they are usually absent from one or more of the three treatments. For the occurrence data, the species generally cluster based on occurrence within treatments. The left cluster in figure 3B shows the seven more abundant species in the clearcuts, the middle cluster shows the 21 species more abundant in selections and checks, and the right cluster the five species only present in the checks. Note that the rare species found only in the checks clustered together regardless of the data used (figs. 3A and B).

Because we also had yearly climate factors affecting the ant community, we used cluster analysis to help us separate out these effects on treatments and ants. Figure 4 shows the cluster analysis and the relative occurrence of species within treatments and years. Although all the clearcuts did not cluster together (rows), those in 1997 and 2000 did, along with selections in 2000. In addition, the selections and checks usually clustered together over all three years, and the extreme flooding year of 1997 did not appear to cluster differently than might be expected. Also, the left cluster of species (columns) is formed mostly by species more abundant in clearcuts, or those with no treatment effects (an exception is *Cam. americanus*, a species that seems to prefer checks). On the other hand, the right cluster of species is made up almost entirely of species more abundant in selection and check stands and those unaffected by treatments. From this analysis there is little evidence that the flooding in 1997 and drought in 2000 affected the ant community beyond the treatment effects noted before.

Treatment Effects on Individual Species

The analysis of treatment effects on individual species using MRPP is shown in table 3 (remember that MRPP is comparing relative species occurrence among and between treatments). Six species liked the selection and check treatments equally well (*Aphaenogaster picea, Cam. decipiens, Cam. pennsylvanicus, Cre. ashmeadi, Cre. minutissima,* and *Pheidole dentata*), and eight had no preferences at all (*A. fulva, A. tennesseensis, Cam. americanus, Hypoponera opacior, Lasius alienus, Ponera pennsylvanicas, Preolepis imparis*, and *Tapinoma sessile*). Although *Cam. americanus* showed no statistically significant preferences here, its three-treatment p-value was almost significant (0.0523), and in the ISA test below it showed

Table 2—Diversity estimates for ants by year and treatments at Pittman Island, Mississippi

	1996			1997			2000			
Diversity measure	Chk	Sel	CC	Chk	Sel	CC	Chk	Sel	CC	Comments
Occurrence	268	362	255	231	257	90	317	233	174	# of occurrences recorded
Species observed	17	19	15	16	16	11	20	18	16	# of species collected
Singletons	4	5	5	4	3	4	2	2	3	only 1 collected
Doubletons	2	1	1	0	0	2	3	3	4	only 2 collected
Chao 2	17.7	20.3	20.0	19.3	17.3	12.7	19.4	18.3	17.0	richness estimator
Jack 2	20.2	23.3	20.8	20.8	19.7	15.5	21.3	19.8	20.0	richness estimator
Bootstrap	18.4	20.6	16.8	17.5	17.3	12.6	20.0	19.2	17.7	richness estimator

Check = Chk, Selection = Sel, and Clearcut = CC.

preferences for checks. Of note, occurrence of the invasive *S. invicta* was significantly different among all treatments, being highest in clearcuts, intermediate in selections, and lowest in checks. *Crematogaster punctulata* showed clear preferences for selections. Finally, *Myrmica spatulata* and *Paratrechina terricola* showed no clear preferences, but gradients across treatments. *Myrmica spatulata* seemed to like checks over selections over clearcuts, while *P. terricola* showed the opposite trend, liking clearcuts over selections over checks.

Indicator Species Analysis

Only eight species were classified as indicators (table 4). The analysis over all three years is perhaps most revealing because it shows species responding to the three treatments consistently, but differently. Four species showed indicator value, *Cam. americanus* and *M. spatulata* for checks, *Cre. punctulata* for selections, and *S. invicta* for clearcuts. In 1996, the first growing season after disturbance, four species had indicator value, *Cre. minutissima* and *Cre. punctulata* for selections, and *H. opacior* and *S. invicta* for clearcuts. However, 1997 is also interesting, with no indicator species identified, perhaps due to the severe flooding that likely moved ants among treatments and affected population and or colony dynamics. Year 2000 shows that after the effects of treatments had stabilized, three species had indicator value, all for checks (*L. alienus, M. spatulata,* and *P. dentata*). Also of

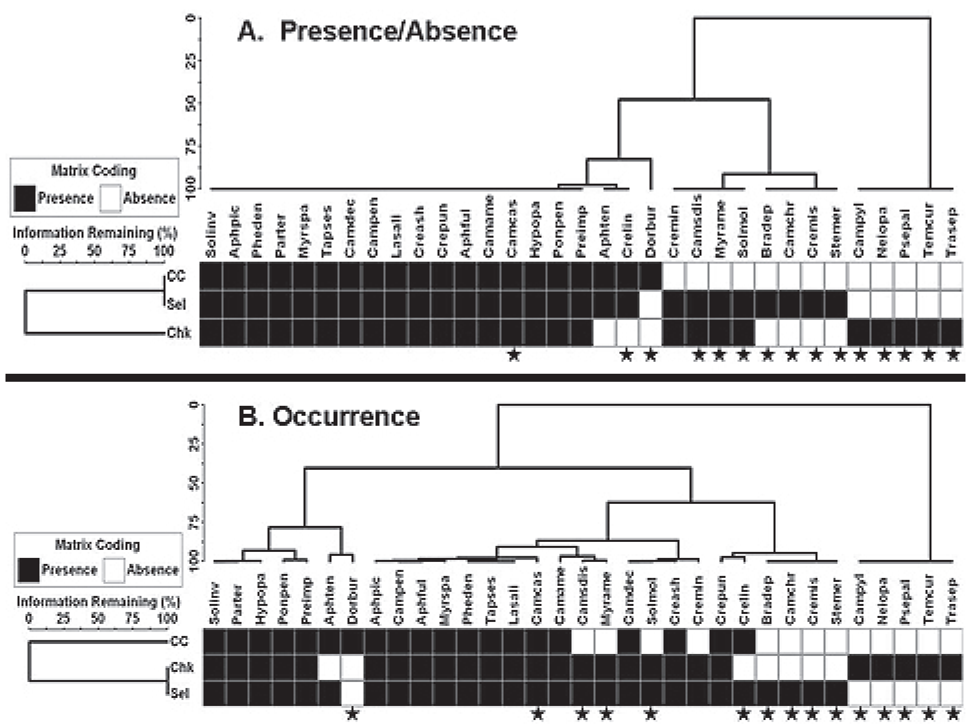

Figure 3—Dendrograms generated by 2-way cluster analysis showing ant diversity as a function of treatment, summed over all 3 collecting years and 3 replications: A) presence/absence data, and B) occurrence data. The 15 rare species are indicated with a star. Species abbreviations include the first 3 letters of the genus and the species. Table 1 has the scientific names. Treatment designations are Check = Chk, Selection = Sel, and Clearcut = CC. Cluster "breaks" are on a sliding scale with a value of 100 being most similar and 0 being very dissimilar. Natural groups have long stems in the dendrogram, and divergent groups are typically linked where the information remaining scale = 0.

importance here is that, by 2000, the invasive *S. invicta* was colonizing all treatments, and lost its ability to indicate severe disturbance (clearcuts), perhaps a clue to the power of this species to use disturbance to its advantage (in this case the ecotones resulting from our treatments).

DISCUSSION

Species richness was generally lower in the clearcuts than in selections and checks (table 2). This response in heavily disturbed sites is comparable to the only other study in the Southern United States on forest harvesting effects on ants. Zettler and others (2004) found decreased species richness following hardwood to pine conversions in South Carolina. Forest disturbance has produced variable results as it relates to species richness in tropical ant studies, decreasing (Schonberg and others 2004, Vasconcelos 1999), increasing (Watt and others 2002) and having no effect (Kalif 2001). Theoretically, opening up the forest may negatively affect forest specialists, while concurrently allowing generalist ants that like disturbance to colonize the sites. However, Palladini and others (2007) and Yi and Moldenke (2005), in studies in Douglas-fir (*Pseudotsuga menziesii*) in the Pacific Northwest, reported increased richness in cutover stands. This difference in the Pacific Northwest occurs because opening up the forest also heats up the ground so that the site is more habitable to cold intolerant ants (Yi and Moldenke 2005, Higgins and Lindgren 2006). Sanders and others (2007) proposed a similar idea, that warmer sites had more ant species along an elevational gradient in the Great Smokey Mountains National Park, U.S.A. Perhaps the opposite effect is true in the hot humid climate of the South, where the ants might instead be seeking shaded sites that are cooler and moister. Certainly the heat-loving *S. invicta* found the clearcuts excellent habitat. This was also the case in South Carolina (Zettler and others 2004), and *S. invicta* dominated the ant community in open grown longleaf pine (*Pinus palustris*) forests undergoing restoration in Louisiana (Colby and Prowell 2006).

Ant occurrence is a similar story. Checks and selections had similar numbers of ants (table 2, occurrence by treatment and year), with reduced numbers in the clearcuts. If it were not for *S. invicta*, the numbers in the clearcuts would have been even lower (table 1). Zettler and others (2004) reported similar results following hardwood to pine conversions in South Carolina. Studies conducted on the effects of forest regeneration in the tropics would suggest that ant abundance is affected little by moderate disturbance (Dunn 2004b, Watt and others 2002).

Even though we found no evidence that short term flooding affected the ant community at Pittman Island, studies in annually flooded Amazonian forests showed that ants were negatively affected (Majer and Delabie 1994, Ribas and Schoereder 2007), and a study of the ants in and around New Orleans, LA, showed species richness decreased by

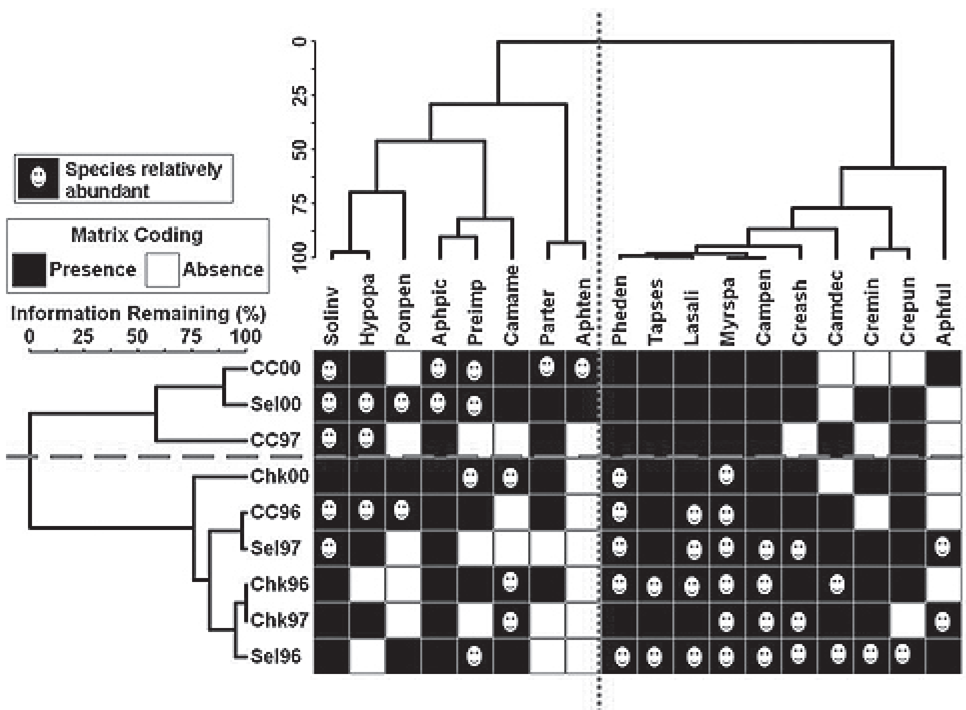

Figure 4—Dendrogram generated by 2-way cluster analysis showing ant diversity as a function of treatment and year (replicates pooled) using the 18 most abundant species. Open circles in the matrix coding shows species that are relatively abundant. Treatment-year designations are: (Check = Chk, Selection = Sel, and Clearcut = CC) followed by year (1996, 1997, and 2000). Cluster "breaks" are on a sliding scale with a value of 100 being most similar and 0 being very dissimilar. Natural groups have long stems in the dendrogram, and very divergent groups are typically linked where the information remaining scale = 0, and are shown here as dashed (- - - - -) and dotted (. . . . .) lines.

Table 3—Treatment effects on common ant species at Pittman Island, Mississippi, as analyzed using the Multi-Response Permutation Procedure

	Treatment Pairs						
	CC-Sel		CC-Chk		Sel-Chk		3 Treatments
Species	#	P	#	P	#	P	P
Aphaenogaster fulva	2 / 6		2 / 6		6 / 6		0.2024
A. tennesseensis	8 / 2		8 / 0		2 / 0		0.3775
A. texana	20 / 74	**0.0152**	20 / 91	**0.0030**	74 / 91	0.5218	**0.0196**
Camponotus americanus	3 / 3		3 / 15		3 / 15		0.0523
C. decipiens	2 / 25	**0.0088**	2 / 25	**0.0069**	25 / 25	1.0000	**0.0245**
C. pennsylvanicus	37 / 84	**0.0213**	37 / 96	**0.0107**	84 / 96	0.0828	**0.0183**
Crematogaster ashmeadi	4 / 31	**0.0024**	4 / 24	**0.0065**	31 / 24	0.5694	**0.0100**
C. lineolata	3 / 36	**0.0019**	3 / 6	0.6491	36 / 6	**0.0061**	**0.0006**
C. minutissima	0 / 26	**0.0047**	0 / 15	**0.0002**	26 / 15	0.2076	**0.0011**
Hypoponera opacior	16 / 9		16 / 3		9 / 3		0.0897
Lasius alienus	53 / 77		53 / 85		77 / 85		0.2288
Myrmica spatulata	41 / 95	0.0742	41 / 163	**0.0001**	95 / 163	**0.0136**	**0.0005**
Paratrechina terricola	52 / 35	0.1243	52 / 7	**0.0216**	35 / 7	**0.0217**	**0.0065**
Pheidole dentata	66 / 131	**0.0410**	66 / 140	**0.0188**	131 / 140	0.5630	**0.0191**
Ponera pennsylvanica	3 / 4		3 / 1		4 / 1		0.5147
Prenolepis imparis	4 / 8		4 / 4		8 / 4		0.4045
Solenopsis invicta	160 / 108	**0.0092**	160 / 38	**0.0000**	108 / 38	**0.0058**	**0.0000**
Tapinoma sessile	41 / 79		41 / 77		79 / 77		0.0934

Check = Chk, Selection = Sel, and Clearcut = CC.
Note: Occurrence (abundance) is represented by # in the treatment pairs, and bold indicates significant differences between treatments at P ≤ 0.05. Species nonsignificant when comparing all 3 treatments were not analyzed further using pairs.

more than 1/2 after flooding from Hurricane Katrina (Wiltz and others 2006).

The cluster analysis of occurrence data showed that the ant communities in the selections and checks were very similar, but differed from the clearcuts. Thus, the act of harvesting is not as important as the degree of tree removal. In our case, cutting all trees (clearcuts) removed food and other habitat resources for ground-active ants that forage on the trunk and in the canopy (Hölldober and Wilson 1990). If standing trees are available for colonization (in our case mostly sugarberry, the same tree species that dominated the uncut check forests) then the ant community appears to be much less affected. Most of the studies on the effects of selection harvesting on ants were done in tropical forests and showed similar results, few effects (Dunn 2004b, Oliver and others 2000, Vanderwoude and others 2000, Vasconcelos and others 2000, Watt and others 2002). In a study of the canopy ants of longleaf pine in Florida, Tschinkel and Hess (1999) found that the ant community responded to increasing tree size, except where a dominant ant species occurred. Likewise, Schonberg and others (2004) discovered that relict trees in pastures were just as species-rich as trees in primary tropical forests in Costa Rica. In addition, rain forest studies (Longino and Colwell 1997) have shown that tree species is not a strong predictor of arboreal ant species richness. So, it is the presence of trees that is important to the ant community, and perhaps the larger the trees the better.

Table 4—Indicator species values of ants with significant values by year for Pittman Island, Mississippi, receiving several harvesting treatments in 1995

	Year											
	All 3 years			1996			1997			2000		
Significant Species	Value*	P	Trt	Value	P	Trt	Value	P	Trt	Value	P	Trt
Camponotus americanus	**47.6**	**0.039**	**Chk**	55.6	0.462		33.3	1.000		54.5	0.532	
Crematogaster minutissima	42.3	0.110		**76.9**	**0.029**	**Sel**	50.0	0.305		71.4	0.139	
C. lineolata	**62.2**	**0.005**	**Sel**	**87.5**	**0.035**	**Sel**	59.3	0.245		38.9	0.418	
Hypoponera opacior	44.4	0.073		**100**	**0.036**	**CC**	42.4	0.502		60.0	0.167	
Lasius alienus	39.5	0.301		36.3	0.612		47.7	0.205		**92.3**	**0.017**	**Chk**
Myrmica spatulata	**54.6**	**0.002**	**Chk**	38.6	0.285		59.8	0.075		**80.6**	**0.032**	**Chk**
Pheidole dentata	41.2	0.183		35.9	0.549		56.1	0.100		**59.0**	**0.036**	**Chk**
Solenopsis invicta	**52.1**	**0.002**	**CC**	**71.6**	**0.023**	**CC**	53.6	0.102		42.2	0.318	

Check = Chk, Selection = Sel, and Clearcut = CC.
Note: Bold indicates significant at p ≤ 0.05. A perfect indicator species would always be present in one treatment and never occur in other treatments, and would have a value of 100.

The MRPP showed that 14 of the 18 ant species analyzed could not differentiate between selections and checks. No species preferred the undisturbed checks exclusively in the MRPP analysis, but when using data over all three study years, the ISA showed two species (*Cam. americanus* and *M. spatulata*) liked the checks. Both the MRPP and ISA showed that *Cre. punctulata* liked the selections, and *S. invicta* liked the clearcuts. By 2000, *L. alienus, M. spatulata,* and *P. dentata* showed preferences for checks. Thus, it would appear that the clearcuts negatively affected three species, and positively affected one. The selection harvesting had little effect on 14 of 18 species analyzed, but benefited *Cre. punctulata*.

Evidently, for those species showing preferences, the checks provide suitable soil moisture and texture, and the downed rotten wood used for nesting. *Camponotus americanus* is reported to nest in soil under logs (Creighton 1950), which is where we have found it nesting in forested sites in Arkansas (unpublished data). *Lasius alienus* and other species in this genus tend root coccids and aphids, preferring well drained soils for nests. We have found it in open and forested sites in bottomland habitats. *Myrmica spatulata* is reported by Creighton (1950) to nest in the soil under objects and to avoid areas of high temperatures and dry conditions. We have not found it in an intensively studied bottomland hardwood site in southeastern Arkansas. We have collected a sister species, *M. punctiventris*, in oaks, but not other forest types at the site. *Pheidole dentata* occurs in a wide range of habitats from forest to beaches, and is one of the most abundant species in the genus in the Southeastern United States (Wilson 2003). It often nests in rotten logs and stumps (Creighton 1950). Why it showed preferences for checks in 2000 is unclear. We have sampled it in open and forested sites in Arkansas.

We have found little information in the literature that would help us understand why *Cre. punctulata* liked the selections. However, the literature is full of information on the preferences for open places by *S. invicta* (Vinson 1997).

Our collecting experience from Arkansas showed us that the presence of a good supply of downed twigs, branches, and logs that are sufficiently rotten, or have lots of “worm holes” inside, provides improved nesting habitat for many species of ants. Although we did not measure the amount of coarse woody debris (CWD) on these treatments, we can generalize that there was much more in the selection and clearcut sites (see fig. 2). This is important because over time this CWD should eventually become suitable nesting habitat for ants. In a study in British Columbia, Higgins and Lindgren (2006) examined the physical attributes of CWD (>10 cm diameter and including stumps) in unharvested and eight to 10 year old harvested pines, as it related to ants. They found no difference in CWD volume among treatments, but in harvested stands CWD was somewhat smaller in diameter, shorter, had less bark, less decay, and was mostly in contact with the forest floor. They reasoned that these factors would likely increase the decay rate and might provide less CWD available to ants over the long run, as compared with unharvested forests.

There is often speculation about how long it might take for the ant community in cutover stands to return to normal. We have no personal experience to support an opinion, but, Palladini and others (2007) argue that in Douglas-fir in Oregon, it might take 100 years for the ant community in a clearcut to return to that of older natural stands. Dunn (2004a) reviewed the ant literature on this issue and concluded that the range is 13 to 40 years in the tropics. In a disturbance study in central Amazonia, Vasconcelos (1999) commented that recuperation of the ground-foraging ant community appeared to be faster than recuperation of the woody-plant community. Although the study of Heneghan and others (2004) was not directly related to ants, they report that it took 21 years for the microarthropod community in a clearcut Appalachian hardwood forest to return to uncut forest conditions. One could surmise that this might indicate the recovery time for ant habitat at our site may be less than 40 years, but will likely be faster than recuperation of the woody-plant community. Only a long-term, or short-term chronosequence study, is likely to assess recovery of ant communities from harvesting disturbances like those in our study.

In conclusion, harvesting affected the ant community somewhat, reducing richness and abundance of some species and increasing it for a few others. The effects from selection cutting were few as compared with clearcutting. Most important, however, was that the red imported fire ant (*S. invicta*), an invasive and exotic species, increased substantially with time in all treatments and may affect the native ants (Lubertazzi and Tschinkel 2003) until the surrounding disturbed treatments grow to the point where the opened forest floor becomes heavily shaded by the growing vegetation, cutting off the heat source to the *S. invicta* colonies. To keep their colony exposed to the sun, we have personally found *S. invicta* nests at Pittman Island on the tops of rotting cut tree trunks lying 1 m off the ground as the ants tried to elude the encroaching shade produced by the vegetation growing from below.

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A MODEL FOR ESTIMATING UNDERSTORY VEGETATION RESPONSE TO FERTILIZATION AND PRECIPITATION IN LOBLOLLY PINE PLANTATIONS

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Abstract—A model form is presented, where the model contains regressors selected for inclusion based on biological rationale, to predict how fertilization, precipitation amounts, and overstory stand density affect understory vegetation biomass. Due to time, economic, and logistic constraints, datasets of large sample sizes generally do not exist for understory vegetation. Thus, we wanted to see if the model form would provide reasonable estimates of understory biomass using a limited range of values for the regressors when estimating parameters.

Data from three loblolly pine (*Pinus taeda* L.) plantations located in the Western Gulf of the Southeastern United States were used to obtain parameter estimates for the biologically derived model form. Stand density index was used as the measure of stand density. Our model predicts that additional amounts of fertilizer and precipitation can increase understory vegetation biomass. However, at some point, depending on precipitation amounts and stand density, increases in fertilization and precipitation will produce decreases in understory vegetation biomass because of simultaneous increases in loblolly pine production. Based on validation results using data from independent studies in the Western Gulf, the model form provides reasonable estimates of understory biomass for regressor values beyond the range used in parameter estimation. Future research needs to concentrate on estimating parameters for the presented model form using a more complete dataset.

INTRODUCTION

Herbaceous vegetation, vines, and shrubs are a major component of nutrient cycles in young pine plantations in Western Gulf Coastal Plain stands of the Southeastern United States (Switzer and Nelson, 1972), add to the biodiversity of these plantations (Miller and Miller 1999, Wolters and Schmidtling 1975), provide wildlife habitat (Miller and Miller 1999, Wolters and Schmidtling 1975), and to some extent forage for domestic animals such as cattle. Understory vegetation also competes with trees for soil water and nutrients, and can detrimentally affect the growth of crop trees (Haywood and others 2003, South and others 2006). Thus, it is imperative to understand how overstory and understory vegetation interact with and affect one another in Western Gulf loblolly pine (*Pinus taeda* L.) plantations.

Studies have shown understory vegetation yield frequently increases in loblolly pine stands in the Western Gulf Coastal region after fertilization (e.g., Brockway and others 1998, Lauer 2003, Thill and Bellemore 1986, Wolters and Schmidtling 1975, Wolters and others 1995). However, increased growth of the overstory trees can eventually shade out the understory vegetation, particularly herbaceous vegetation. Many models have been developed to estimate the relationship between pine overstory density and understory vegetation using basal area per unit area in the Southeastern United States (Gaines and others 1954, Grelen and others 1972, Grelen and Lohrey 1978, Halls and Schuster 1965, Wolters 1973, Wolters 1982, Wolters and Schmidtling 1975, Wolters and others 1982). Mengak and others (1989) developed models to estimate understory yield in natural and planted loblolly pine stands using age as the independent variable in the Piedmont of SC. Despite all of these models, none were developed to estimate understory biomass in pure loblolly pine plantations in relation to stand density, let alone, response to fertilization in pure loblolly pine plantations. Additionally, other than Mengak and others (1989), all of these models predict herbaceous (grass and grass-like and forb) production and estimates do not include shrub production or biomass. Thus, there is a need to develop a more complete model to reasonably predict understory vegetation response to fertilization in Western Gulf loblolly pine plantations. All future reference to biomass refers to living, aboveground standing biomass.

Density Management Diagrams (DMDs) are available for loblolly pine in the Southeastern United States (e.g., Williams 1994, Dean and Chang 2002); however, no DMDs have graphically related understory biomass to overstory stand density. Vales and Bunnell (1988) found that Stand Density Index has a strong relationship with the transmission of light through canopy. Moore and Deiter (1992) is the only publication that we are aware of that relates understory vegetation to Stand Density Index; however, the study was conducted in the Pacific Southwest. By using Stand Density Index (Reineke 1933) to predict understory vegetation biomass, DMDs can be used to determine how an overstory objective may potentially affect understory biomass and hence affect wildlife and domestic animals (VanderSchaaf 2006), carbon budgets, etc.

The first objective of this paper was to develop a biologically meaningful model form sensitive to fertilization rates and precipitation amounts to predict understory vegetation biomass in pure loblolly pine plantations using Stand Density Index as the measure of overstory density. Due to time, economic, and logistic constraints, large sample size sets of understory vegetation data are usually not available. Thus, a second objective is to determine whether the model form will provide reasonable estimates of understory biomass when extrapolating beyond the range of regressor values used in parameter estimation.

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METHODS

The relationship between overstory loblolly pine density and understory vegetation was studied in response to fertilization at three cutover sites in the Western Gulf Coastal Plain two years after treatment (table 1). This study was part of a larger study looking at the effects of fertilization on loblolly pine growth (Forest Nutrition Cooperative 2003). Results from this understory vegetation study have been previously reported (McKnight and Heitzman 2004, McKnight 2005). Sites were located near Hermitage, AR, north of Leesville, LA, and near DeKalb, MS. All plantations were owned by forest industries; the AR site was owned by Potlatch Corporation, the LA site was owned by Forest Capital Partners, the MS site was owned by Plum Creek Timber Company. No thinning treatments were conducted at any site. The Hermitage, AR site soil was classified in the Stough series and is a coarse, loamy, siliceous, thermic Fragiaquic Paleudults. Site preparation consisted of a chemical treatment in September 1995 using 12 ounces of Arsenal (53.1 percent imazapyr) and 2 quarts of Accord (53.8 percent glyphosate) followed by a broadcast burn. Planting occurred in the 1995-1996 season. A first year herbaceous weed control treatment occurred in April of 1996 using 4 ounces of Arsenal and 2 ounces of Oust (75 percent sulfometuron methyl). The Leesville, LA site was classified in the Sacul series and has a fine, smectitic, thermic Chromic Dystraquerts soil and site preparation consisted of a broadcast burn followed by a Savannah plow in October of 1993. Planting occurred in the 1993-1994 season. A first year herbaceous weed control treatment was conducted using 4 ounces of Arsenal and 2 ounces of Oust. The DeKalb, MS site soil was classified in the Smithdale series and is a fine, loamy, siliceous, subactive, thermic Typic Hapludults. Site preparation consisted of a chemical site preparation in August of 1995 using 16 ounces of Arsenal and 1.5 quarts of Accord. Planting occurred in the 1995-1996 season.

Precipitation data for 2001 were obtained for all sites from AWIS (2001). See McKnight (2005) for the dominant understory species, based on percent cover values and visual observation, by lifeform and by site.

Loblolly Pine Measurements

All overstory measurements used in the model were performed during the winter months of 2000-2001. Loblolly pine measurement plots ranged in size from 0.03 to 0.08 ha, were surrounded by a 14 m buffer on all sides, and each contained a minimum of 60 trees at time of establishment. Nitrogen was applied by hand at rates of 0, 67, 134, 202, and 269 kg/hectare. Additionally, P was applied at a constant proportional rate of 10 percent to the N rate. At the DeKalb, MS site only, boron (B) was applied at a constant proportional rate of 0.005 percent to the N rate. A randomized block design was used, where each site had two blocks of the complete set of the 5 fertilizer rates. Measurements included diameter-breast height and total height.

Stand Density Index (SDI) was calculated using equation [1]:

$$\mathrm{SDI} = \mathrm{TPH}\left(\frac{\mathrm{QMD}}{25.4}\right)^{1.6} \qquad [1]$$

Where:
TPH – trees/ha
QMD – quadratic mean diameter (cm)

Values of SDI used in the understory model ranged from 279 to 402 at the Hermitage, AR site, from 338 to 461 at the DeKalb, MS site, and from 370 to 558 at the Leesville, LA site.

Understory Vegetation Biomass Measurements

During the last two weeks of August 2001, two 1-m^2 biomass plots were systematically established in both replications (blocks) of the four fertilization treatments and the control at each site to sample understory biomass. All living understory vegetation rooted within the 1-m^2 plot was hand clipped at ground level. These samples were taken to the laboratory at the University of Arkansas-Monticello and oven dried at 60 °C for 48 hours. After the samples were dry, they were weighed to determine oven-dry biomass. The average of the two samples per fertilizer rate, replication (block), and study site combination was calculated and used to fit the model. Therefore, a total of 30 observations were used (3 locations x 2 blocks per location x 5 rates = 30 plots). Other models to predict understory vegetation yield in relation to overstory density have used comparable sample sizes (e.g., Gaines and others 1954, Grelen and others 1972, McConnell and Smith 1970, Mengak and others 1989, Uresk and Severson 1989, VanderSchaaf 1999).

Statistical Analysis

The dependent variable in our study is the total amount of living, above-ground, understory vegetation biomass (grasses and grass-likes, forbs, woody vines, and shrubs) in mid- to late August. Least squares regression analysis was conducted to estimate parameters using PROC MODEL of SAS Institute Inc. (1988); the Gauss-Newton algorithm was used for non-linear model forms. Several different models were tested which included non-transformed, and natural logarithmic, square root, and exponential transformations of dependent and independent variables. For the linear model forms tested, transformations of the dependent variable and Stand Density Index were conducted since a negative curvilinear relationship between these two variables has been strongly and widely established (Jameson 1967, Uresk and Severson, 1989, VanderSchaaf 1999, Wolters and Schmidtling 1975).

SDI, rates of fertilizer, and precipitation during the period of March until the sampling date in August (in cm), were selected to be included in the model. The total amount of precipitation during these months was selected because this is often considered to be the growing season for most herbaceous, vine, and shrub species, and loblolly pine in this region. Regressors and regressor forms were selected based on biological rationale which is explained more fully in the Discussion below. The mean of the untransformed absolute value of the residuals (MR) was used to contrast and compare candidate model forms fitted using the data described above. Residual errors were examined for trends in the data and the coefficients of the regressors were examined to make sure they had biological meaning and were significantly different from zero at the alpha = 0.05 level.

Table 1—Understory vegetation biomass study establishment age, minimum, mean, and maximum understory vegetation biomass, Precip--amount of precipitation during the period from March until the sampling date in August (AWIS, 2001), Average--average amount of annual precipitation (NOAA, 2004) during the period from March until August from 1960 to 2001, Std. Dev--standard deviation of the amount of annual precipitation (NOAA, 2004) during the period from March until August from 1960 to 2001, and soil drainage where SPD -- somewhat poorly-drained, WD -- well-drained, and MWD -- mostly well-drained

		Understory vegetation biomass (kg/hectare)						
Site	Age	Min	Mean	Max	Precip (cm)	Average (cm)	Std. Dev (cm)	Drainage
Hermitage, AR	5	618	1186	1947	78.66	67.32	15.74	SPD
DeKalb, MS	5	1535	2428	3627	92.18	72.70	21.82	WD
Leesville, LA	7	262	519	1005	78.33	68.51	19.77	MWD

Site	Age	YST	QMD (cm)	TPH	SDI	BA (m^2)	Average HT (m)
Hermitage, AR	3	0	5.6	1254	112	3.1	3.7
	5	2	11.2	1236	331	12.1	5.7
DeKalb, MS	3	0	5.4	1621	135	3.7	4.0
	5	2	10.5	1616	394	14.0	6.8
Leesville, LA	5	0	7.7	1774	263	8.3	5.9
	7	2	10.8	1764	450	16.2	8.2

Overstory loblolly pine average plot-level characteristics by site are also given. Where: YST--years since treatment (0 -- at time of fertilization), QMD--quadratic mean diameter, TPH--trees per hectare, SDI--stand density index (metric), BA--basal area/ha, Average Ht--average total tree height of all trees.

Model Validation

As a means of determining the predictive ability of our model form (eq. 2) for independent populations vastly different than those used in model fitting, we compared estimated understory vegetation biomass (table 2) from equation 2 to published understory vegetation biomass values (Blair and Enghardt 1976, Lauer 2003). Precipitation data from March to August for the Blair and Enghardt (1976) study were obtained from the Woodworth 2 SE weather station (NOAA 1957, NOAA 1962, NOAA 1967, NOAA 1969). Precipitation data during the months of March to August for the years of 1987 and 1988 were obtained from NOAA (NOAA 1987, NOAA, 1988) using the Merrill and Atmore weather stations for the MS and AL sites, respectively (Lauer 2003). For the Blair and Enghardt (1976) study, understory vegetation was measured at ages 30, 35, 40, and 42. Although we can compare our estimates to their understory vegetation values, there are some complications that need to be addressed. First, basal area/ha and trees/ha were obtained from graphs, and quadratic mean diameter was calculated using the values of basal area/ha and trees/ha. Second, they measured "current season's growth" rather than measuring standing biomass as in our study. For herbaceous vegetation this is not a major concern, but shrub annual production and shrub total standing biomass can differ greatly. Third, they merely state that samples were taken in late summer and do not give specific dates. Thus, we assume measurements were taken in mid- to late August. Fourth, a substantial midstory of hardwoods existed on the site which probably affected understory vegetation yield. The study by Lauer (2003) examined the impacts of first year fertilization, first year herbaceous vegetation control, and combinations of these factors on understory biomass in pine plantations. Understory biomass was determined one and two years after loblolly pine plantation establishment on a site in the MS county of George and a site in Escambia County, AL.

RESULTS

Equation 2 was the model form selected which we believe best predicts understory biomass in relation to fertilization rate, precipitation amounts, and overstory stand density based on both biological and statistical considerations:

$$\text{LnTotal} = -20.0312 - 0.02987\text{LnPrecip}*\text{SDI}^{1/2} + 0.000177\text{Fert}*\text{Precip} + 6.656713\text{LnPrecip} - 0.00015(\text{SDI}^{1/2}*\text{Fert}*\text{LnPrecip}) \quad [2]$$

Where:
Total = total understory biomass (grasses and grass-likes, forbs, woody vines, and shrubs) in mid to late August (kg/ha)
Ln = natural logarithm
Precip = total amount of precipitation from the beginning of March until the site-specific sampling date in August (cm).
SDI = stand density index (metric)
Fert = rates of fertilization (kg/ha) – since P rates are proportional to N rates, N rates are the regressor variable.
Adj. R^2 = 0.8324, MR = 285.1, n = 30

The model explained a large amount of variation in understory vegetation biomass. Standard errors of the parameter estimates are: (Intercept) -- 4.4174, (LnPrecip*$\text{SDI}^{1/2}$) -- 0.0148, (Fert*Precip) -- 0.000075, LnPrecip -- 1.1790, ($\text{SDI}^{1/2}$*Fert*LnPrecip) -- 0.000072. Model forms (e.g., square root transformations of the dependent and independent variables rather than natural logarithm transformations) other than equation 2 had inferior statistical or biological properties compared to equation 2 such as

Table 2—Comparison of predicted values using eqn. (2) and observed data from a thinning study conducted in a loblolly pine plantation in central LA (Blair and Enghardt, 1976) and from a first year herbaceous vegetation control and fertilization study conducted in loblolly pine plantations (it is assumed the plantations had 0 Stand Density Index) in MS and AL (Lauer, 2003)

Site	Year	Treatment	Age	SDI	Precip (cm)	Observed (kg/ha)	Predicted (kg/ha)	Error (kg/ha)
Thinning Study	1957	.	30	592	88.19	241	687	-446
	1957	.	30	536	88.19	310	804	-494
	1957	.	30	446	88.19	335	1056	-721
	1962	.	35	575	63.73	370	104	266
	1962	.	35	493	63.73	338	130	208
	1962	.	35	403	63.73	299	170	129
	1967	.	40	497	81.92	777	579	198
	1967	.	40	432	81.92	759	706	53
	1967	.	40	368	81.92	720	872	-151
	1969	.	42	464	82.98	756	692	64
	1969	.	42	403	82.98	742	840	-98
	1969	.	42	339	82.98	690	1045	-355
George, MS	1987	Control	1	0	71.04	3188	4222	-1034
		NP	1	0	71.04	6855	7434	-579
		HC	1	0	71.04	1584	4222	-2638
		NP+HC	1	0	71.04	1830	7434	-5604
		NPK	1	0	71.04	7393	7434	-41
		NPK+HC	1	0	71.04	798	7434	-6636
	1988	Control	2	0	90.86	2788	21721	-18933
		NP	2	0	90.86	2570	44790	-42220
		NPK	2	0	90.86	2770	44790	-42020
Escambia, AL	1987	Control	1	0	64.31	2565	2176	389
		NP	1	0	64.31	3638	3633	5
		HC	1	0	64.31	835	2176	-1341
		NP+HC	1	0	64.31	1303	3633	-2330
	1988	Control	2	0	63.98	2506	2103	403
		NP	2	0	63.98	3036	3501	-465
		HC	2	0	63.98	1643	2103	-460
		NP+HC	2	0	63.98	2296	3501	-1205

Where: Year--year of sampling, Treatment--[Control -- no fertilization or herbaceous vegetation control, NP -- N and P fertilization at a rate of 45 kg/ha and 56 kg/ha; respectively, NPK--in addition to NP, a K fertilization at a rate of 112 kg/ha, HC--first year herbaceous weed control treatment. For the NP and NPK treatments, a rate of 45 was used for the fertilizer rate in the model], SDI--stand density index (metric), Precip--amount of precipitation from March to August, Observed--understory vegetation data from Blair and Enghardt (1976) or Lauer (2003), Predicted--estimated understory vegetation using eqn. (2)

non-significant variables or poorer estimates of understory biomass across the range of SDI.

Based on the validation analyses and a general examination of model estimates (table 2 and fig. 1), a more complete dataset composed of more sites, sampling across several years thus allowing precipitation to vary at one site, a greater range of stand densities, etc., is needed to better estimate understory biomass across a range of site conditions. For example, when greatly extrapolating beyond the values of the regressors used in fitting equation 2, particularly extreme value combinations of the regressors used in the model, predictions are very poor. In many cases though, equation 2, fitted using a limited dataset, is robust enough to account for extreme limits of one and in some cases even two regressors [extreme overstory densities (SDI less than 200/ha), high rates of N (greater than 330 kg/ha), and high rates of March to August precipitation (greater than 92 cm)], but using extreme limits for three regressors will result in large overpredictions. Additionally, low rates of March to August precipitation (less than 55 cm) can potentially result in large underpredictions of understory biomass. Predictions using low values of SDI (less than 200) are reasonable for low fertilization rates, but low SDI in combination with higher rates of fertilizer and March to August precipitation produce large errors in understory biomass prediction. Herbaceous weed and site preparation treatments can greatly limit the applicability of our model, especially at lower stand densities. A reasonable maximum amount of understory production in these stands probably ranges from 6000 to 7000 kg/ha (Lauer 2003).

DISCUSSION

Biological Rationale behind Regressors in the Model

Our current model predicts that increases in precipitation (Grelen and Lohrey 1978, Wolters 1982) and fertilizer rate (Basile 1970, Bowns 1972) positively affect understory biomass -- Fert*Precip and LnPrecip regressors. Studies have showed the positive interaction between fertilization and moisture for understory yield (Bowns 1972, Riegel and others 1991, Thill and Bellemore 1986). The model form provides for additional amounts of understory production with increasing rates of fertilizer as precipitation becomes greater.

However, positive effects on understory vegetation following increases in fertilization and precipitation, and the synergistic interaction between fertilization and precipitation, are offset by increased growth rates of the overstory (Allen 1987), particularly crown production (King and others 1999, Vose and Allen 1988, Yu and others 1999), following additional amounts of precipitation and following fertilization treatments (Brockway and others 1998, Haywood and others 2003, Wolters and Schmidtling 1975, Wolters and others 1995). Increases in overstory production will reduce light to the understory and induce more competition for nutrients and moisture between overstory trees and understory vegetation. Plus, as stand density increases, greater amounts of nutrients become tied up in the overstory tree biomass (Borders and others 2004) that includes tree stems, crown branches and twigs, and roots that can further reduce nutrient availability to the understory vegetation. In addition to the negative aspects of the overstory on understory vegetation in terms of competition for resources, increases in needle cast associated with greater crown production following continually greater rates of fertilization may smother understory production (Haywood and others 2003). These overstory-understory vegetation biological interactions are represented by the negative coefficients for the LnPrecip*SDI regressor, and the three-way interaction regressor between SDI, fertilizer rate, and precipitation amount. Estimates from equation 2 show that overstory density produces the greatest change in understory vegetation production. Predictions show

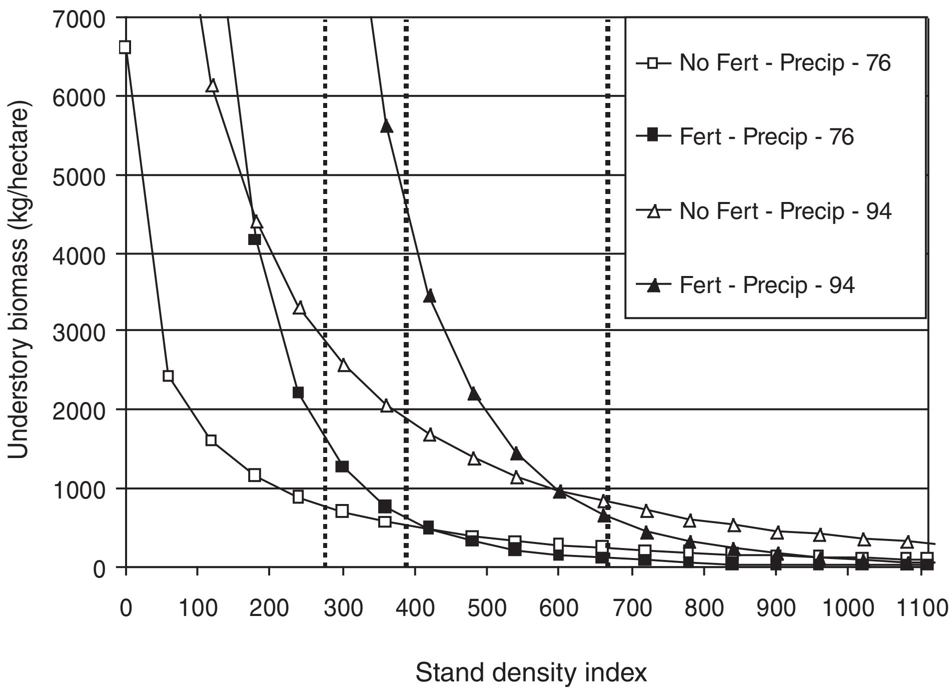

Figure 1—Estimated total understory biomass (kg/ha) for a control and a fertilization treatment of 269-27 kg/ha N, and P; respectively, over Stand Density Index. Where: solid symbols – fertilization treatments, open symbols -- no fertilization, Precip. is the amount of precipitation (in cm) during the month of March until the sampling date in August. The dashed lines are management zones of a DMD developed by Dean and Chang (2002). The lines are at SDI values of 278 (Canopy closure -- 25 percent of Maximum size-density relationship of 1110), 388 (Full-site occupancy -- 35 percent of 1110), and 666 (Threshold of self-thinning -- 60 percent of 1110).

that relatively greater overstory densities, regardless of the rate of fertilization or large amounts of precipitation, produce low understory vegetation biomass consistent with Haywood and others (2003).

Extrapolation of the Model beyond the Range of Stand Densities Used in Parameter Estimation

A negative curvilinear relationship between understory vegetation production and overstory stand density has been strongly and widely established (Jameson 1967, Uresk and Severson 1989, VanderSchaaf 1999, Wolters and Schmidtling 1975). Although our current model is based on data from plantations ranging in age from 5 to 7, we believe our model form can be used to reasonably predict understory vegetation biomass and response to fertilization treatments for ages greater than seven due to the negative curvilinear relationship. Certainly, as with most models, predicted values using equation 2 will never, beyond chance, coincide exactly with observed values. Obviously, silvicultural practices such as mid-rotation herbaceous or brush control, severe thinning, repeated fertilization treatments, etc. will limit the applicability of the model. However, when no other tool is available, model extrapolation can be useful. Based on the validation results from the study by Lauer (2003), our current model in certain instances can provide reasonable estimates of understory biomass following fertilization treatments conducted at ages younger than five.

Parameters in our current model were estimated using a SDI range from 279 to 558. At SDI values greater than these, the negative curvilinear relationship continues to decrease understory biomass (fig. 1). As stand density increases, although the percent error [(Predicted-Observed)/Observed] may continue to be large or even increase, the practical magnitude of the error decreases. For example, a 100 percent error in biomass prediction at high stand densities has little impact practically since the magnitude of the error will be small and will therefore have little effect on estimated stocking rates.

CONCLUSIONS

A model form developed based on biological rationale was presented to predict understory vegetation biomass in relation to fertilization rates, precipitation amounts, and overstory stand density. A limited dataset from loblolly pine plantations was used to estimate parameters of the presented model form. Based on validation results, and when using constraints on the regressors as discussed in the paper, our model form appears to provide reasonable estimates of understory biomass and response to N and P fertilization for regressor values outside the range used in parameter estimation. Partially based on this current analysis, we believe overstory density, fertilizer rates, and precipitation amounts are more important factors in determining understory biomass and response to fertilization in loblolly pine stands than plantation age (Bowns 1972, Riegel and others 1991, Thill and Bellemore 1986, VanderSchaaf and others 2002, Haywood and others 2003). Future research should concentrate on fitting equation 2 using a more complete dataset in terms of overstory stand density, precipitation amounts, stand ages, fertilization rates, and repeated measures. Additionally, future research should concentrate on obtaining understory data from studies using non-proportional rates of N and P and perhaps from studies quantifying multi-nutrient fertilization effects on understory biomass.

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DELAYED MORTALITY OF EASTERN HARDWOODS AFTER PRESCRIBED FIRE

Daniel A. Yaussy and Thomas A. Waldrop[1]

Abstract—The Southern Appalachian Mountain and the Ohio Hills sites of the National Fire and Fire Surrogate Study are located in hardwood dominated forests. Mortality of trees was anticipated the first year after burning but it continued for up to 4 years after burning, which was not expected. Survival analysis showed that the likelihood of mortality was related to prior tree health, size class, species, and first-order fire effects. Both sites were unmanaged and trees were likely stressed by competition. Burning provided additional stresses through cambial and crown damage which may have predisposed trees to death. This study indicated that monitoring only first-year effects of prescribed fires or wildfires does not provide an accurate assessment of fire impacts. Also, managers should consider tree health when making plans for prescribed burns.

INTRODUCTION

Several studies document the cellular necrosis of tree cambium and buds directly due to the heat of combustion (i.e., first-order fire effects) after fuel-reduction treatments. However, none has attempted to establish the interactions between fuel reduction and ecological processes. The National Fire and Fire Surrogate (NFFS) Study was established to compare ecological and economic impacts of prescribed fire and mechanical fuel-reduction treatments (Youngblood and others 2005). Thirteen independent study sites across the United States (eight in the West and five in the East) receive identical treatment (prescribed fire and mechanical fuel reduction treatments) and measurement protocols. All western sites are dominated by ponderosa pine (*Pinus ponderosa*). Eastern sites include hardwood-dominated sites in the Ohio Hill Country and Southern Appalachian Mountains of NC, a pine-hardwood site in the Piedmont of SC, a site dominated by longleaf pine (*P. palustris*) in AL, and a site dominated by slash pine (*P. elliottii*) in FL.

Two NFFS sites—the Southern Appalachian Mountain and Ohio Hills sites—are located in hardwood-dominated forests. Increased first-year post-treatment mortality of overstory trees (d.b.h.>4 cm) was expected in Southern Appalachian Mountain and Ohio Hills units that received prescribed fire. Not expected was that these units would display increased mortality in trees of most size classes for up to 4 years post-treatment. The causes of delayed mortality are unknown but are thought to be related to prior tree health, species related bark thickness, and first order fire effects. This study examines the relationship of fuel, fire behavior, and tree variables to delayed mortality of hardwoods.

METHODS

Study Sites

Both the Southern Appalachian and Ohio Hills study sites consist of three replicate blocks, with four fuel reduction treatments applied to a randomly chosen treatment unit within each block. The Ohio Hills NFFS site is located on the unglaciated Allegheny Plateau of southern Ohio. The climate of the region is cool, temperate with mean annual precipitation of 1 024 mm and mean annual temperature of 11.3 °C (Sutherland and others 2003). The forests of the region developed between 1850 and 1900, after the cessation of cutting for the charcoal and iron industries (Sutherland and others 2003). The current canopy composition differs little from that recorded in the original land surveys of the early 1800s. The most abundant species in the current canopy were white oak (*Quercus alba*), chestnut oak (*Q. prinus*), hickories (*Carya* spp.), and black oak (*Q. velutina*); however, the midstory and understory are now dominated by species that have only in the last few decades become common in this community (e.g., sugar maple (*Acer saccharum*) red maple (*A. rubrum*), and yellow-poplar (*Liriodendron tulipifera*) (Yaussy and others 2003). Analysis of fire scars in stems of trees that were cut very near the NFFS experiment indicated that fires were frequent (return intervals of 4-8 years) from 1875 to 1930 (McEwan and others 2007). In contrast, few fires occurred after the onset of fire suppression activities in the mid 1920s (Hutchinson and others 2002). The Ohio Hills NFFS site is composed of three experimental blocks, with one each in the Raccoon Ecological Management Area, Zaleski State Forest, and Tar Hollow State Forest.

The Southern Appalachian NFFS site is located in the Green River Game Land in the Blue Ridge Physiographic Province, Polk County, North Carolina. The climate of the region is warm continental, with mean annual precipitation of 1,638 mm and mean annual temperature of 17.6 °C (Keenan, 1998). The forests of the study area were 80 to 120 years old, and no indication of past agriculture or recent fire was present, though the historical fire return interval prior to 1940 was approximately 10 years (Harmon 1982). The most abundant species in the canopy were northern red oak (*Q. rubra*), chestnut oak, white oak, black oak, pignut hickory (*Carya glabra*), mockernut hickory (*C. tomentosa*), and shortleaf pine (*Pinus echinata*). A relatively dense evergreen shrub assemblage was present in the understory of a majority of the study site, with mountain laurel (*Kalmia latifolia*)and rhododendron (*Rhododendron maximum*) the most common species.

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Treatments and Experimental Design

Each of the three replicate blocks in each site is composed of four treatment units. At the Ohio Hills site, individual treatment units were 19-26 ha whereas in the Southern Appalachian site they were approximately 14 ha in size. A 50 by 50 m grid was established in each treatment unit, and ten sample plots of 0.10 ha were established randomly within each treatment unit.

Treatments were randomly allocated among treatment units at each site. Treatments consisted of prescribed fire, a mechanical treatment, the combination of prescribed fire and mechanical treatments, and an untreated control. In the Ohio Hills, the mechanical treatment involved thinning from below to a basal area comparable to that present prior to Euro-American settlement. This was a commercial thinning operation that reduced basal area from 27.0 to 20.9 m^2/ha. At the Southern Appalachian site, the mechanical treatment was designed to create a vertical fuel break. Chainsaw crews removed all stems >1.8 m tall and <10.2 cm diameter at breast height (d.b.h.) as well as all mountain laurel and rhododendron stems, regardless of size. All detritus generated by the mechanical treatments was left on site in both areas.

Mechanical treatments were accomplished between September 2000 and April 2001 in Ohio and between December 2001 and February 2002 at the Southern Appalachian site. The prescribed fires were applied during March-April 2001 in the Ohio Hills and March 2003 at the Southern Appalachian site. These dormant-season fires consumed unconsolidated leaf litter and fine woody fuels while leaving the majority of the coarse woody fuels only charred. At the Southern Appalachian site, the fire prescription was also designed to kill ericaceous shrubs. Details of fire behavior are given by Iverson and others (2004) for the Ohio Hills and Tomcho (2004) for the Southern Appalachian site.

Measurements and Analysis

All treatment units were sampled during the pretreatment year, 2000 in the Ohio Hills and 2001 in the Southern Appalachians. Additional measurements were made in Ohio 1, 2, and 4 years after treatment. The Southern Appalachian site was measured 1 and 3 years after treatment. Numerous variables were measured at grid points and sample plots for many components of the NFFS study. Those used in this study included peak fire temperature, crown vigor, bark thickness, duration of heat, d.b.h., basal area, and dummy variables (0 or 1) for mortality, treatment, and species. Most variables were measured in accordance with standard protocols. Peak temperature and duration of heat were measured with thermocouples attached to dataloggers buried at each grid point. We measured a total of 6,941 trees at the two sites, and 546 of these trees died during the study. A survival analysis was conducted using the SAS® PHREG procedure with Cox regression and Stepwise procedures. This analysis produces the probability of survival given each measured condition for each variable.

RESULTS

Several variables proved to have significant relationships to hardwood mortality. The hazard function (table 1) provides a relative measure of the relationship of each variable to predicting mortality. A value of 1 indicates no change. The index for maximum temperature suggests that for each degree that fire temperature increases, there is a 0.3 percent increase in the probability of mortality each year. The probability of mortality decreases by 4.5 percent with each increase of bark thickness by 1 mm. The single most important predictor of mortality was crown vigor. The survival rate for healthy trees was 3.69 times the survival rate for trees of low vigor.

The relative contribution of individual variables in determining mortality varied over the 4-year sampling period. There was little difference between long-term mortality in OH and long-term mortality in NC (fig. 1). However, treatment did affect survival (fig. 2). The probability that a tree would die within 4 years was 5 percent in plots that had received the burn-only treatment and 7 percent if the plots had received the mechanical + burn treatment. Peak fire temperature also had an impact (fig. 3). Trees subjected to temperatures of 100 °C had a 96 percent chance to survive 4 years but trees subjected to 700 °C had an 80 percent chance to survive. Preburn tree vigor is a strong predictor of mortality (fig. 4). Healthy trees had a 95 percent chance of surviving 4 years after fire while trees with low vigor had less than a 73 percent chance. Exposure to increased heat for 20 minutes had slightly more impact on long-term survival than did exposure to increased heat for 1 minute (fig. 5). D.b.h. and bark thickness had predictable effects (fig. 6); small diameter trees with thin bark had a 92 percent rate of survival, whereas larger trees with thick bark had a 99 percent survival rate. With all other variables held constant, there were differences in survival rates among species (fig. 7). Oaks were less likely to survive 4 years than were maple, blackgum, and sourwood.

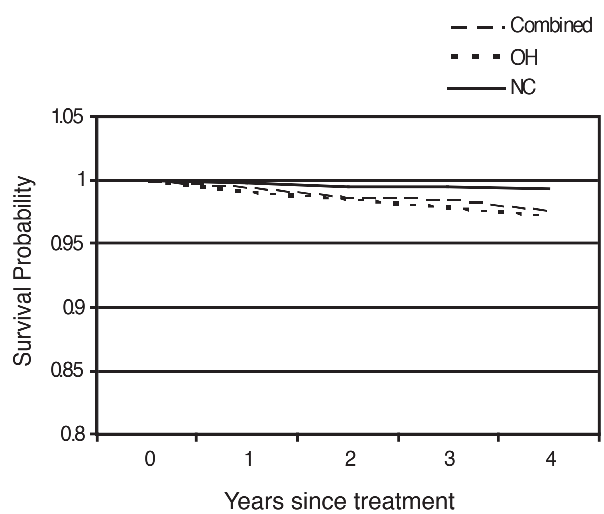

Figure 1—Differences in the survival probability of hardwoods after prescribed fires at the Southern Appalachian and Ohio NFFS sites.

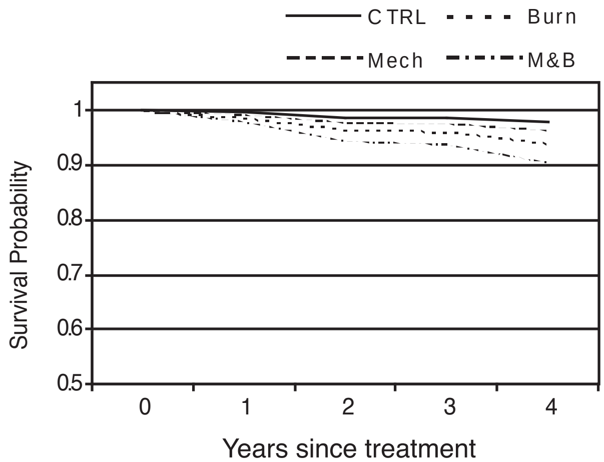

Figure 2—Differences in the survival probability of hardwoods by fuel reduction treatment at the Southern Appalachian and Ohio NFFS sites.

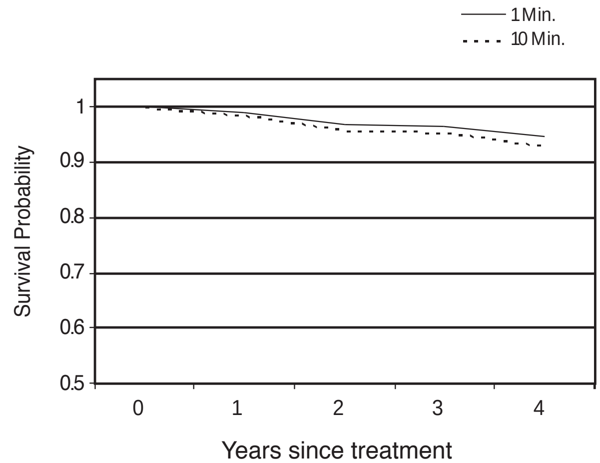

Figure 5—Differences in the survival probability of hardwoods by duration of exposure to heat at the Southern Appalachian and Ohio NFFS sites.

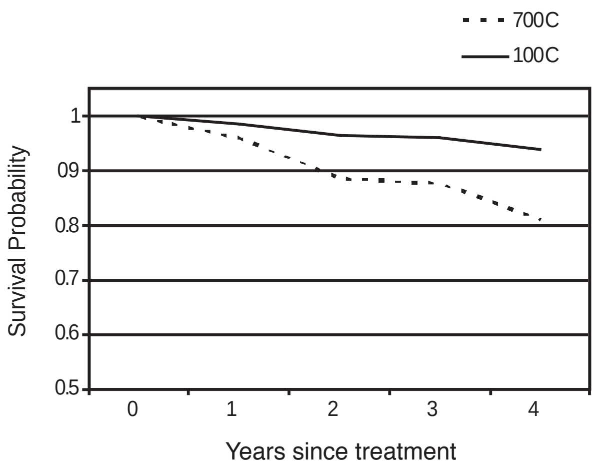

Figure 3—Differences in the survival probability of hardwoods by peak fire temperature at the Southern Appalachian and Ohio NFFS sites.

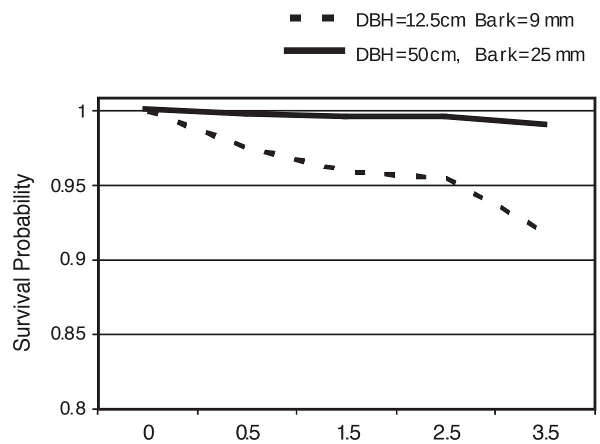

Figure 6—Differences in the survival probability of hardwoods by dbh and bark thickness at the Southern Appalachian and Ohio NFFS sites.

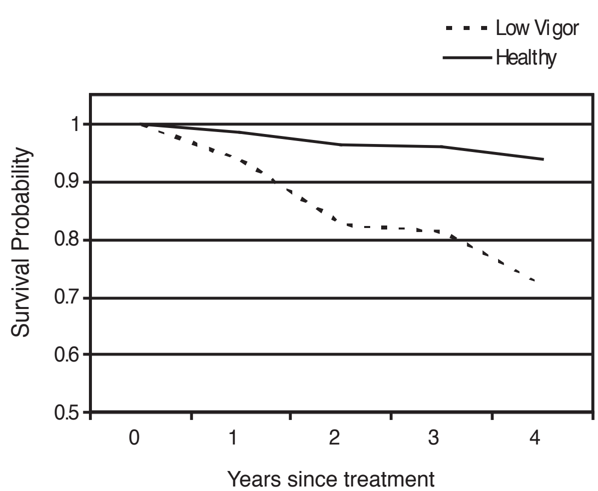

Figure 4—Differences in the survival probability of hardwoods by pre-burn tree vigor class at the Southern Appalachian and Ohio NFFS sites.

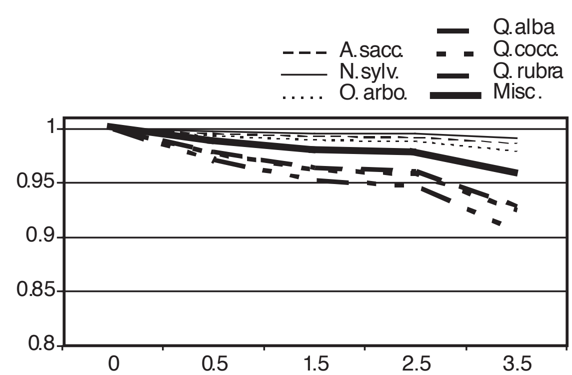

Figure 7—Differences in the survival probability of hardwoods by tree species at the Southern Appalachian and Ohio NFFS sites.

The probability of survival for any given tree is a function of all of the variables shown here and likely many more. If a tree is subjected to more than one of these variables, survival probability decreases dramatically. For example, a small tree has an 8 percent chance of dying in 4 years; that same tree has a 23 percent chance of dying if it also has low vigor. If the tree is subjected to 700 °C for 20 minutes, its chance of dying would increase to 88 percent.

CONCLUSIONS

In this study, mortality of hardwood species was observed for up to 4 years after prescribed burning at two study sites of the National Fire and Fire Surrogate Study. The pattern of mortality was similar at both sites, suggesting that conclusions drawn in earlier reports may have been premature. A number of variables were related to mortality but the most important ones were the peak temperature of the fire, the duration of exposure of each tree to flames, preburn tree vigor, and bark thickness. These variables were tested separately but they probably interact with each other and with a large number of variables not measured. Secondary agents of decline may be pathogens such as *Phytophthora* and *Armillaria, root* diseases present at both sites but not a component of this study. Microsite differences may play a role in the decline if burning dries the soil by increasing sunlight and decreasing forest floor depth (Waldrop and others 2002). Both sites were unmanaged and trees were likely stressed by competition. Burning provided additional stresses through cambial and crown damage which may have predisposed trees to death. Additional research is needed to fully understand the full complex of biotic and abiotic variables that contribute to hardwood mortality after fire.

ACKNOWLEDGMENT

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A range of issues affecting southern forests are addressed in 113 papers. Papers are grouped into 12 sessions that include carbon; pine silviculture; invasive species; site preparation; hardwood artificial regeneration; longleaf pine; forest health and fire; growth and yield; hardwood intermediate treatments; hardwood natural regeneration; wildlife; and posters.