EXPLORING NATURAL AND ARTIFICIAL REGENERATION TECHNIQUES FOR

DEVELOPING HIGH-QUALITY BOTTOMLAND OAK STANDS

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Troy Sherwood Taylor

Certificate of Approval:

Greg Somers
Associate Professor
Forestry and Wildlife Sciences

Edward F. Loewenstein, Chair
Assistant Professor
Forestry and Wildlife Sciences

Arthur H. Chappelka
Professor
Forestry and Wildlife Sciences

B. Graeme Lockaby
Professor
Forestry and Wildlife Sciences

Stephen L. McFarland
Acting Dean
Graduate School

EXPLORING NATURAL AND ARTIFICIAL REGENERATION TECHNIQUES FOR DEVELOPING HIGH-QUALITY BOTTOMLAND OAK STANDS

Troy Sherwood Taylor

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Troy Sherwood Taylor

Signature of Author

Date

THESIS ABSTRACT

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Troy Sherwood Taylor

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Bottomland hardwood forests of the southeastern United States are among the most diverse and productive in the country. In the past, many of these areas were not managed soundly for timber production and, as a result, are currently stocked with a variety of species that are commercially less valuable than oak. Naturally regenerating oak in bottomland forests is problematic because large advance reproduction is absent in the understory, and the silvicultural techniques that favor oak development encourage the growth of problematic species such as *Rubus* spp., *Vitis* spp., *Smilax* spp., and *Arundinaria* spp. These and other shade-tolerant woody and herbaceous species deprive oak of light during critical periods of establishment, often causing them to die. This study examines the impacts of pre-harvest treatments applied one year in advance of

overstory removal to determine if this is a sufficient amount of time to establish natural oak reproduction when there is a good acorn crop, or if this is enough time to allow artificially regenerated seedlings to overcome transplant shock such that they can be competitive once the overstory is removed. Also examined were various types of browse protection and fertilization on the growth and establishment of seedlings planted after a commercial clearcut. Our findings indicate that preharvest treatments to increase understory light levels and decrease the abundance of vines prior to overstory removal is essential for increasing the stocking and competitive stature of naturally regenerated oak seedlings. Underplanting oak prior to overstory removal is a viable option to increase stocking and/or control spatial distribution of desirable stems. Where pre-harvest regeneration planning is not a viable option, the site should be clearcut and some measure of site preparation employed. Planted seedlings should be fertilized and protected using plastic tree shelters. Not only do seedlings become established more rapidly, but their form is far superior to those open-grown or in wire tree shelters. Initial planting costs are higher for such cultural treatments, but the cost per established seedling is less than those unprotected or encircled by wire shelters and will result in shorter rotations.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

Bottomland hardwood forests in the Southeast are among the most diverse and productive in the United States (Gresham 1985, Kennedy and Johnson 1985, Clatterbuck 1987). One of the most prominent species groups found in these forests is Oak (*Quercus* spp.), which are represented by more than a dozen different species. The importance of this group is not limited to the production of high-quality timber (Kennedy and Johnson 1985), or that their mast crops are an important food staple for many species of birds and mammals (Christisen and Korschgen 1955, Hirsch and Segelquist 1978, Hurst and Dickson 1992, Miller et al. 1999, Clark 2004). The uses of this group include fuel, tannin, extractives, and lumber (Young and Young 1992). Of the oaks found in bottomland forests two of the most highly coveted due to their excellent form and superior quality are cherrybark (*Q. pagodifolia* Ell.) (Krinard 1990) and Nuttall (*Q. nuttallii* Palm.) (Filer 1990) oaks. Both, in general, have long, straight boles with the potential to produce excellent sawtimber in about 70 years.

As commercially important as these species are the areas where they have naturally occurred is shrinking due to pressures from a growing and increasingly non-rural populations (Sheffield and Dickson 1998). Bottomland hardwood forests are projected to decline by 1.8 million acres by 2040, and hardwood harvests are expected to exceed growth by 2025 (Southern Environmental Law Center 2002). Compounding this forecast is the fact that the areas where these oaks are found have not been previously managed for quality timber production (Clatterbuck and Meadows 1993) largely because they are a result of agricultural abandonment and subject to periodic flooding. Abusive agricultural practices followed by natural reversion to forest cover resulted in areas where the species mix was commercially undesirable (Kays et al. 1985, Arthur et al. 1997). Since then these areas have been periodically highgraded with only the most valuable stems removed leaving variable sized gaps in the canopy (Wilder et al. 1999). These intermittent openings allowed enough light to reach the forest floor that the growth and development of faster growing, undesirable species was initiated (Chambers and Henkel 1989). The understory is much more vigorous in these areas and has higher proportions of shade tolerant species than previously stocked them (Lantagne et al. 1990). Forests that were once dominated by high-quality oak stems are now stocked with a variety of species that are less desirable commercially (McGee 1986, Johnson 1993, Walters 1993, Belli et al. 1999, Clatterbuck et al. 1999), and the form and quality of preferred species such as the oaks are typically poor (Clatterbuck and Meadows 1993).

Despite their reputation for quality timber and prominence in many forests, oaks are surprisingly difficult to regenerate (Crow 1992). On highly productive mesic sites typical of bottomland hardwood forests, oak is more difficult to regenerate than in more xeric ecosystems (Johnson 1993). In mesic systems, the presence of undesirable, shade-tolerant woody and herbaceous species create a dense cohort of taller vegetation that deprive oak seedlings of light and resources during a critical period of establishment (Carvell and Tryon 1961, Smith 1984, Buckley et al. 1998,), causing them to die. With little silvicultural intervention, the proportion of oaks in the upper stratum are reduced and that of undesirable species (e.g. *Ulmus* spp., *Carpinus caroliniana*, *Carya* spp., etc.) increasing over time (Aust et al. 1985, Heiligmann et al. 1985, Hix and Lorimer 1991, Buckley et al. 1998). This is problematic because oak is being lost as a seed source as the number and regeneration potential of vigorous, shade-tolerant competitors increases (Sander and Smith 1989, Johnson 1993, Clatterbuck et al. 1999,). Since most associated species in bottomland stands are of lower commercial value than oak, it is important to ensure that this species will be a significant component of new stands following harvest (Graney 1989).

In order to increase the proportion and competitive stature of oak on mesic sites typical of bottomland hardwood forests, the numbers and size of advance reproduction must be increased to enhance their ability to grow rapidly in height after release (Loftis 2004). This often is a difficult goal because oak advance reproduction does not accumulate beneath mature stands on mesic sites because of the dense shade produced by the midstory (Loftis 1983, Johnson et al. 2002). For this reason, it is generally accepted that the shelterwood method is the most reliable silvicultural system available to naturally regenerate oak and increase the stocking and size of oak regeneration (Smith 1986, Nyland 1996). This technique, when properly executed, leaves trees that not only have desirable phenotypic character as a seed source but also provide enough canopy cover to protect regeneration and mitigate sensitive environmental conditions (Nyland 1996). Current stand prescriptions to increase oak stocking, however, call for treatment from 3-10 years prior to overstory removal to be successful (Sander 1979, Johnson et al. 1986, Loftis 1990, Spetich et al. 2004). This can be problematic from an operational standpoint for a number of reasons that include: how quickly the landowner needs money vs. the necessary time required accumulating the desired amount of advance reproduction (Dey and Parker 1996), and the periodicity of acorn crops (Young and Young 1992). In situations where natural oak regeneration cannot compete or where no seed source is available, land managers will likely see the need to incorporate some degree of artificial regeneration to improve the stocking and density of future crop tree in order to meet their diverse goals (Hix and Lorimer 1991, Spetich et al. 2004).

There is some evidence that newly generated oak seedlings can grow competitively with other tree species in southern bottomland forests (Golden and Loewenstein 1991), but silvicultural techniques t favoring oak development also encourage the growth and development of problematic species such as *Rubus* spp., *Vitis* spp., *Smilax* spp., and *Arundinaria* spp. (Janzen and Hodges 1984, Kormanik et al. 1995). These species can impart a developmental disadvantage on oak because they can rapidly create a dense mat of vegetation that completely covers oak reproduction (Smith 1984). Oak seedlings unable to penetrate through this layer of competition usually die because they are not able to secure the resources necessary for plant growth (Buckley et al. 1998, Belli et al. 1999). The presence of these species in southern forests, especially vines, can be especially problematic in managing high quality crop trees (Smith 1986) because of their ability to elongate rapidly and use other plant stems as a ladder to facilitate their climb into the upper canopy (Smith 1984). When grapevines invade tree crowns, especially in young stands (Trimble and Tryon 1979), they can cause stem deformities whereby the potential for future production of quality timber products is severely reduced (Smith 1984).

The slow initial height growth of oak seedlings not only makes them vulnerable to vegetative competition, but also to animal browse. Castleberry et al. (1999) found that until seedlings are able to grow above 1.25 m they are susceptible to browse pressure from white-tailed deer (*Odocoileus virginianus* Zimm.) because they are a preferred browse species. Intense browsing has adversely affected commercially important tree species in other forest types leading to a less desirable species composition in terms of both commercial value and forage quality (Anderson and Loucks 1979, Tilghman 1989, Walters 1993).

Efforts to protect seedlings from browse damage led to the invention of plastic tree shelters (Tulley 1985). These translucent tree shelters were approximately 1.2 m tall, allowed some light penetration, provided seedlings with a favorable microclimate, and protection from herbivory (Manchester et al. 1988). Research in Michigan has shown that tree shelters increased oak seedling survival and early height growth (Lantagne et al. 1990); comparable tests in North Carolina, Pennsylvania, and Connecticut confirmed these results (Manchester et al. 1988, Walters 1993, Ward et al. 2000). In the South, the effectiveness of tree shelters with planted oak has been investigated in urban environments (Jones et al. 1996, West et al. 1999) and on abandoned agricultural fields (Schweitzer et al. 1999) with excellent success. Survival and growth of bottomland oaks have been enhanced on cutover upland/bottomland transition zones in eastern Alabama (Dubois et al. 2000), but we are unaware of any published reports regarding the effectiveness of tree shelters on the establishment of bottomland oak species on recently harvested southern bottomland forests.

Although our knowledge regarding natural oak regeneration has significantly increased in recent years, there remains an inadequate understanding of the causal factors that influence regeneration success or failure. This study explores natural and artificial regeneration techniques for developing high-quality bottomland oak stands. The impacts of pre-harvest treatments applied one year in advance of overstory removal were observed to determine if this is a sufficient amount of time to establish natural oak reproduction when there is a good acorn crop, or if this is enough time to allow artificially regenerated seedlings to overcome transplant shock such that they can be competitive once the overstory is removed. The efficacy of various types of browse protection and fertilization on seedling growth and establishment success also was observed in a southern bottomland hardwood forest to determine if artificially regenerating quality oak is a viable option.

II. QUANTIFYING THE EFFECTS OF PREHARVEST TREATMENTS ON THE GROWTH OF NATURAL AND ARTIFICIAL OAK REPRODUCTION

ABSTRACT

Past abusive practices and rapid growth of competitive species have depleted areas of southern bottomland hardwood forests of high-quality oak (*Quercus*) species. Current prescriptions indicate that pre-harvest treatments must be implemented as least five years in advance of overstory removal to maintain or increase the proportion of oak. A two-year study was established in 2000 in a mature bottomland oak forest in west Alabama to examine the influence of pre-harvest treatments applied one year in advance of overstory removal on the growth of both natural oak seedlings and underplanted Nuttall oak (*Q. nuttallii* Palm.) seedlings. The treatments included: control, midstory reduction, and midstory reduction plus vine treatment. Although there were no statistically significant differences between the treatments, natural oak seedlings, planted seedlings, and other commercial species were all 10-20% taller than non-commercial species. In addition, stocking of desirable species increased in the understory reduction plus vine treatment plots compared to either of the other treatments. Based on our data, pre-harvest enrichment planting one year prior to overstory removal coordinated with harvesting during a good mast year can improve the spatial distribution and species composition toward that is more commercially valuable.

INTRODUCTION

Bottomland hardwood forests in the southern United States are highly productive areas that have high species diversity and richness. Oaks (*Quercus* spp.) are one of the most prominent species groups to be found in these habitats and are represented by more than a dozen different species. While there are still many areas that contain quality stems, for the most part these forests have not been managed soundly for quality timber production. Abusive agricultural practices followed by periodic highgrading removed the most valuable stems and left behind gaps in forest canopies that allowed for faster-growing, shade tolerant species to become established. Today, the forests once dominated by high-quality stems currently are stocked with scattered stems with poor form (Clatterbuck and Meadows 1993) and a variety of commercially undesirable species (Johnson 1993, Clatterbuck et al. 1999). Compounding this situation is the fact that studies in both northern (Heiligmann et al. 1985, Hill and Dickman 1988, Hix and Lorimer 1991) and southern states (McGee 1986, Graney 1989) have had only moderate and unpredictable success in securing oak reproduction after regeneration harvests. As southern bottomland hardwood forests mature and are considered for harvest, the question of how to successfully regenerate them so that they contain a greater proportion of high-valued species, such as Nuttall oak (*Q. nuttallii* Palm.), than what they are currently stocked with becomes imperative.

To naturally regenerate shade-tolerant species such as oak, it is generally accepted that the shelterwood method is the most reliable system. This technique, when properly executed, leaves trees that not only have desirable phenotypic character as a seed source but also provide enough canopy cover to protect regeneration and mitigate sensitive environmental conditions (Nyland 1996). Stand prescriptions to increase oak stocking call for treatments periods ranging from 3-10 years prior to final harvest to be successful. This can be problematic from an operational standpoint for at least three reasons: 1) the economic situation of the landowner. The decision to harvest trees often is made when money is needed for a variety of reasons, and many people cannot wait up to ten years to pay bills that are due today; 2) scheduling a harvest. The success of preharvest treatments is difficult to analyze unless the areas are closely monitored which may not be feasible from an economic standpoint, especially if multiple treatments are necessary; and 3) implementation of the shelterwood method is dependent on the periodicity of good acorn crops. Since oak mast crops are every 4-10 years (Young and Young 1992), this creates a situation where scheduling treatments and harvests to coincide with this event extremely difficult.

There is some evidence that newly generated oak seedlings can grow competitively with other tree species in southern bottomland forests (Golden and Loewenstein 1991), but the silvicultural techniques favoring oak development often create conditions that not only encourage the growth of non-desirable woody stems, but also promote the development of problematic species such as *Rubus* spp., *Vitis* spp., *Smilax* spp., and *Arundinaria* spp. These species can impart a developmental disadvantage on oak because they can rapidly create a dense mat of vegetation that completely covers oak reproduction. Oak seedlings not able to penetrate through this layer of competition usually die because they are unable to secure the resources necessary for plant growth (Buckley et al. 1998, Belli et al. 1999). The presence of these species in southern forests, especially vines, can be especially problematic in managing high quality crop trees (Smith 1986) because of their ability to elongate rapidly and use other plant stems as a ladder to facilitate their climb toward the sun. When vines attach themselves to young seedlings they are capable of pulling them over as the main stem elongates and are an important factor contributing to poor bole form.

For all of these reasons, the feasibility of implementing a treatment one year in advance of final harvest was observed to determine if this is a sufficient amount of time to establish natural oak reproduction when there is a good acorn crop, or if this is enough time to allow artificially regenerated seedlings to overcome transplant shock such that they can be competitive once the overstory is removed. Specifically, the stocking of natural seedlings was monitored to determine population trends. The growth and development of natural and artificially regenerated seedlings was observed within three experimental preharvest treatments: control, understory reduction, and understory reduction plus vine removal.

MATERIALS AND METHODS

Study Site

This study was conducted in a bottomland oak forest adjacent to the Tombigbee River in Sumter County, near Bellamy, Alabama. The site is located at approximately 32.5°N, 88ºW and the study was implemented in the summer of 2000. Nearly fifty percent of the pre-treatment basal area was oak (*Quercus* spp.), 25% sweetgum (*Liquidambar styraciflua* L.), with the other 25% comprised of other overstory and subcanopy tree species (Table 1). White oaks were not a significant component of this forest, and comprised less than 5% of the overstory population. Soils are deep, well-drained, nearly level, and are of the Alamuchee-Mooreville complex with soil texture ranging from sandy loam to silty clay loam (USDA Soil Conservation Service 1989). Although these areas can be inundated for short period, the study areas did not flood over the course of this experiment. Average annual rainfall is 149 cm, and the average daily temperature ranges from 11ºC to 25ºC (Southern Regional Climate Center 2004).

Experimental design and treatments

In summer 2000, three 2.5 ha sites were located in a mature bottomland oak forest. At each site, a grid was established (80 m by 241 m) and partitioned into six treatment areas measuring 40 m by 80 m. Three survey strips were centered in each of the treatment areas, consisted of 20 contiguous square plots (2 m by 2 m), and separated by approximately 5 meters for a total of 60 plots per treated area. Supplementing the study design was the underplanting of forty 1-0 bareroot Nuttall oak seedlings within each treatment area in spring 2001 (Figure 1). Four rows of ten seedlings were hand planted with planting bars at 15 m by 15 m spacing in rows to either side and in between survey strips. There were a combined total of 18 randomized treatments areas (Figure 2), in which 1080 seedling inventory plots were installed and 720 Nuttall oak seedlings planted.

Three understory treatments were examined in the completely randomized design of the experiment, and were: (1) control, no management action, (2) understory reduction, basal injection of Arsenal™ and RoundUp Pro™ that targeted undesirable species ≤ 15 cm dbh, and (3) understory reduction combined with vine reduction, where, in addition to the understory reduction treatment, vine foliage was treated with a 4% (by volume) solution of RoundUp Pro™ applied at a rate of 1.0 l/ha. In cases where vines were large and woody, they were manually severed and cut surfaces treated with the Arsenal™ mixture. Treatments were applied late fall 2000 after the natural seedling inventory was complete. In winter 2001 all three 2.5 ha research areas were clearcut.

Measurements

Initial data from the seedling inventory plots were collected in late summer 2000. Treatments were applied after the inventory was completed in fall 2000 prior to leaf senescence. These data were gathered again in fall 2001, prior to the commercial clearcuts in winter 2001, and again in fall 2002. The numbers of seedlings were recorded for each seedling inventory plot by species and size class category (based on seedling height): (1) 0-15 cm, (2) 15-30 cm, (3) 30-90 cm, and (4) > 90 cm, up to 3.8 cm dbh (1.2 m).

In addition, the relative abundance of non-woody species (Vitis, Berchemia, Smilax, and Arundinaria) was recorded based on visual estimates of plot coverage using the following categories: (1) <10%, (2) 10-25%, (3) 25-50%, and (4) > 50%. These data were gathered in fall 2000, 2001, and 2002.

Groundline diameter and heights of underplanted Nuttall oak seedlings were measured using calipers and meter stick in March 2001 one week following planting, and first year growth was recorded in fall 2001. In spring 2002, after the winter harvest, the planted oaks were classified based on their condition following harvest (M = missing, or unable to locate, R = alive/resprout, A = alive, good condition, and D = dead).

Statistical Analysis

Analyses of variance (ANOVA) was performed on pretreatment natural seedling inventory data to determine if there were differences in the number of species present, stocking, frequency of stems, or stem heights across the treatment areas for each of three species groups: oak, commercial species not including oak, and non-commercial species (Table 2).

Repeated Measures ANOVA (RM-ANOVA) was used to evaluate any interactions (time x species x treatment) among the cultural treatments based on stocking and height of woody stems in milacre plots. Woody stem analysis was broken down into the same three species groupings listed above. Also evaluated in the same manner were any changes in average plot coverage of *Arundinaria* spp., *Berchemia* spp., *Smilax* spp., and *Vitis* spp. by treatment. Stocking based on the species' presence or absence in seedling inventory plots using the same methodology.

ANOVA was used to examine if there were treatment differences in height and diameter growth of underplanted Nuttall oak seedlings after one growing season. Post-harvest seedling conditions by treatment were tested by Chi-square criteria using logistic regression techniques.

RESULTS

Pre-treatment analyses

Baseline seedling inventory data indicate that there were no significant differences between treatment areas based on the number of species present, frequency of occurrence, average seedling heights, or stocking of the major species groups prior to treatment application.

Stocking of woody stems

The stocking of seedling inventory plots was analyzed using repeated measures analysis of variance with time of measurement (pre-treatment, post-treatment/pre-harvest, and post harvest) and species groups as within-subjects factors. The main effect of time was significant ($P < 0.0001$), as was species group (oak, commercial species, and non-commercial species) and a time by species interaction ($P < 0.0001$ and $P < 0.0001$, respectively). Treatment effects were not statistically significant over the course of the study ($P = 0.1675$). Post-hoc comparisons were performed using M-matrix contrasts. The stocking of each species group dropped significantly after treatments were applied (2000-2001) ($P < 0.0001$ for each species group) (Table 3), but there was no change in the stocking among the groups ($P = 0.5399$) when combined over time. After the harvest (2001-2002), stocking for the oak and commercial species groups increased dramatically ($P < 0.0001$) while that of non-commercial species continued to decline. From the start of the experiment to one season after harvest (2000-2002) there were no significant differences in stocking of commercial species ($P = 0.7790$), but stocking of oak was significantly enhanced ($P = 0.0002$) and non-commercial species declined ($P < 0.0001$).

Heights of woody stems

Heights of seedlings in inventory plots were also analyzed using repeated measures analysis of variance with time of measurement (pre-treatment, post-treatment/pre-harvest, and post harvest) and species groups as within-subjects factors. In order to use RM analyses, categorical height data was transformed into continuous data using stem frequencies and size class midpoints (e.g. stems in the 0-15 cm size class were assigned a value of 7.5 cm, etc.) to determine the average. The main effect of time was significant ($P = 0.0048$), as was species group (oak, commercial species, and non-commercial species) and a time by species interaction ($P < 0.0001$ and $P = 0.0033$, respectively). Treatment did not significantly affect average seedling height over the course of the study ($P = 0.6526$). Post-hoc comparisons were performed using M-matrix contrasts. The average heights for commercial species dropped significantly from 2000 to 2001 ($P = 0.0036$), while heights for oak and non-commercial species remained relatively stable ($P = 0.0737$ and $P = 0.1180$, respectively) (Table 3). After the harvest (2001-2002), average heights for all groups combined showed no significant differences ($P = 0.6025$). Over the span of the experiment (from 2000 to 2002), there were no significant differences in the height of non-commercial species ($P = 0.6732$), but heights of both commercial species and oaks displayed significant gains ($P = 0.0094$ and $P = 0.0005$, respectively).

Stocking of non-tree competition

Stocking of non-tree competition in seedling inventory plots was analyzed using repeated measures analysis of variance. The main effect of time was not significant ($P = 0.2545$), but species group (Arundinaria, Berchemia, Smilax, and Vitis) was significant as was the time by species interaction ($P < 0.0001$ and $P < 0.0001$, respectively). Treatment did not significantly affect the stocking of non-tree competition over the course of the study when simultaneously tested ($P = 0.1675$). Post-hoc comparisons for examining individual species' stocking and percent cover were performed using M-matrix contrasts. From 2000-2001, the stocking of Smilax was significantly reduced ($P = 0.0015$) while the stocking of Arundinaria, Berchemia, and Vitis was unchanged ($P = 0.2839$, $P = 0.7880$, and $P = 0.0855$, respectively). Following harvest (2001-2002), there was no change in the stocking of Arundinaria ($P = 0.5419$), but the stocking of Berchemia rose ($P < 0.0001$) while that of Smilax and Vitis dropped ($P < 0.0001$ and $P = 0.0380$, respectively). From 2000-2002, stocking of Arundinaria remained unchanged ($P = 0.4510$) while Berchemia significantly increased ($P = 0.0006$) and Smilax and Vitis declined ($P < 0.0001$ and $P = 0.0046$, respectively)

Plot coverage of non-tree competition

The percent coverage of non-tree competition in seedling inventory plots was analyzed using repeated measures analysis of variance with time of measurement and species groups as within-subjects factors. In order to use RM-ANOVA the percent cover data were transformed into continuous data by assigning values to the categorical value of each plot (e.g. if cover was determined to be 10-25% for a plot, then a value of 12.5 %

was used for that plot), and then the mean percent cover for each treatment determined. The sphericity assumption was met, and the main effect of time was not significant (P = 0.8589), but species group was significant as was the time by species interaction (P < 0.0001 and P < 0.0001, respectively). Treatment did not significantly affect the stocking of non-tree competition over the course of the study (P = 0.6837). Post-hoc comparisons were performed using M-matrix contrasts. From 2000 to 2001, none of the species groups experienced changes in plot coverage (P = 0.5885, P = 0.4910, P = 0.6613, and P = 0.4086 for Arundinaria, Berchemia, Smilax, and Vitis, respectively). Following the harvest (2001-2002), stocking of Berchemia rose significantly (P < 0.0001) while Arundinaria stocking dropped significantly (P = 0.0131). During the same period, stocking of both Smilax and Vitis did not change significantly (P = 0.0646 and P = 0.6818, respectively). From 2000 to 2002 there were no significant differences in plot coverage for Smilax and Vitis (P = 0.0627 and P = 0.9468, respectively, but stocking of Arundinaria was significantly lowered (P = 0.0175), while that of Berchemia increased (P < 0.0001).

Underplanted Nuttall oak seedlings

After one growing season, ANOVA results indicate that there were no significant treatment effects on groundline diameter growth (P = 0.8447), but there were differences in height growth (P = 0.0087). Seedlings in the understory reduction and understory reduction plus vine treatments grew 210% and 170% more in height than those in the control group, respectively. After one growing season the survival rate was 96.4% across all treatments. Chi-square analyses were used to determine the effect of harvesting on planted seedlings (missing, alive-resprout, alive-good condition, or dead), and whether the effects differed between treatments. The data indicate that there were significant differences in the condition of seedlings following harvest based on which treatment they received (P = 0.0197), and statistical contrasts further reveal that seedlings in either of the treated areas experienced fewer instances of mortality than did seedlings in control areas (P = 0.0450). There were no other significant differences among post-harvest seedling condition categories. Of the 720 seedlings planted, 200 (27.8%) were alive and in good condition, 60 (8.3%) were alive but had resprouted, 57 (7.9%) were identified as dead, and the remaining 400 seedlings (56.0%) were unable to be located after harvest.

DISCUSSION

The stocking of all woody stems dropped considerably after treatments were applied and before overstory removal, which was to be expected. However, after harvest the resulting stocking trend differences between each species group were quite remarkable. The commercial species group returned to the same level of stocking when baseline measurements were recorded at the onset of the study. Stocking of oak species increased dramatically during the experiment, from 70% stocking when baseline measurements were taken to about 95% after the overstory was removed. This might attributed to the large acorn crop combined with oak reproduction that were already present in the understory, but was not measured. The increase in oak stocking did vary but corroborates with previous studies in southern hardwood forests (Aust et al. 1985, Graney 1989) where stands initially start with tremendously high numbers of oak seedlings. What is most interesting, perhaps, is what occurred with the stocking of non-commercial species. Once treatments were applied, the stocking of non-commercial species decreased as the other groups; however, it appears that they have yet to recover to their pre-treatment baseline levels. When baseline measurements were recorded the non-commercial species group averaged about 90% stocking when the overstory was removed declined to 62% stocking. This goes against what occurs in many areas, where there usually is an influx of low-value, faster growing, pioneer species (McGee 1986, Hill and Dickman 1988, Hix and Lorimer 1991, Lorimer et al. 1994). While the reason for this is unknown, there appears to be at least two possible explanations: (1) the abundance of oak seedlings reduced potential growing space that normally would be colonized by the non-commercial species group, and/or (2) another site variable which was not measured had changed so that the area was not as hospitable for non-commercial species. Although no data were collected, it appeared that there was more water onsite than prior to the harvest due to a substantial reduction in transpiration rates. The standing water and subsequent short-term anaerobic conditions may have inhibited many non-commercial species from germinating and limited their establishment success, whereas the oak and commercial species did not appear to have been adversely affected.

Although there were no statistically significant differences in natural seedling heights by treatment, heights of seedlings in all three species groups increased at least slightly over the course of this experiment. After the third measurement period, mean heights of seedlings in the non-commercial group remained stable, while heights of commercial species and oaks had increased significantly (20% and 35%, respectively). One of the most interesting aspects of this is that height gains of seedlings of commercial species dropped after treatments were applied and increased only aafter the overstory was removed, while height increases of oak occurred over the course of the study. This is likely attributed commercial species inadvertently targeted when treatments were applied.

The stocking of non-woody competition was highly variable throughout the three research areas. Arundinaria remained unchanged over the course of the experiment while stocking of Berchemia more than doubled. While the reasons for this are uncertain, it seems plausible that these species are more easily overlooked and, in some areas where they had been established, some areas simply were not treated effectively. The stocking results for Smilax and Vitis, however, are much different than the other two species. Here, there was a dramatic drop in stocking by nearly 50% that can largely be attributable to their visible presence throughout the study areas. Since they were easily identifiable, and tended to be aggregated, they perhaps were targeted more readily during treatment application.

The proportion of plots covered with vines and other competition did not vary much as a whole, but there were species that were affected over the course of the study. The percentage of plots covered with Smilax and Vitis did not experience any statistically significant changes, but that of Arundinaria dropped and Berchemia increased. Again, this may be due to the wet site conditions after overstory removal. The fact that Vitis did not decrease in plot coverage may be an important point that needs further exploration, because Graney (1989) reported that in stands with high site index there is a surge of herbaceous vegetation and vine development. This is important to note. In southern bottomland hardwood forests *Vitis* spp., more than the others examined, have the potential to influence woody stem form for many years due to their ability to attach to and climb up a tree stem to reach the upper canopy. When this occurs, the vines can grow so large in a short time that they are able to bend terminal leaders and cause stem deformities. Since plot coverage remained stable for vines over the course of the study, it may mean that our herbicide application was not entirely successful at controlling them. Even if the treatment was only partially effective, it may allow natural oak reproduction to more quickly establish a good root system making them more competitive. If this occurs, they will undergo rapid shoot elongation earlier than untreated areas making it more difficult for the vines to influence stem form.

Oak seedlings planted in treatment areas had greater vertical growth rates and increased survival rates after harvest compared to those planted in control areas. Our results agree with previous studies where natural (Chambers and Jenkins 1983) and artificially regenerated (Nix et al. 1984) oak seedlings benefit from increased light before the overstory was removed. This period allows oak the opportunity to establish their root systems so height growth can be enhanced after harvest. Although 55% of the underplanted seedlings in our study were destroyed or missing since overstory removal, it seems that planting bareroot seedlings one year prior to harvest is ample time for them to overcome transplant shock and a feasible option for land managers. There still is the opportunity that most of the 260 surviving seedlings grow to maturity, which roughly equates 35 crop trees ha^{-1} over the study area. While this would not fully stock a stand with oak, it is an excellent way to supplement natural regeneration during good mast years and provide some assurance as to the spatial distribution of crop trees.

CONCLUSIONS

The results of this experiment indicate that either of the understory treatments examined were beneficial for the oaks and other commercial species, but were unfavorable for the non-commercial species groups. Based on the stocking and height growth trends seen in the data, it appears that the significance of non-commercial species is declining while that of the oak and other commercial species is increasing. Treatment effects on stocking of non-woody competitor species also was not statistically significant ($P = 0.2560$), but there were significant effects that were dependent on the species examined. Of particular importance in this study is Vitis due to its ability to spread rapidly across large areas and their potential to negatively influence oak stem form (Smith 1986). In this study, the stocking of Vitis was reduced even though the overall percent plot coverage apparently was unaffected. Even if this is a short-term trend that only lasts for one or two growing seasons, it may be beneficial for desirable species. If the oak and other commercially valuable species can capitalize on available resources during this time, it appears from our data that treatments increasing understory light levels can aid in precipitating a shift in species composition toward one that is more desirable in terms of better form and commercial value. This is in agreement with Lorimer et al. (1994), who examined the impact of tall and low understory vegetation removal on oak seedling development. They suggest that any type of cultural treatment that increases understory light levels likely has some benefit in increasing the stature and competitiveness of natural oak seedlings. If a landowner desires to improve the species composition in bottomland mixed hardwood forests toward one dominated by oak and other commercial species that some treatment reducing mid-story light levels be applied at least two years in advance of overstory removal. In addition, landowners should plant of 50 high-quality oak seedlings ha^{-1} to supplement natural regeneration and improve the spatial distribution of crop trees. Although this initially may appear to be prohibitive in terms of cost and labor, the benefits of these actions will be a more commercially valuable species mix and a shorter rotation compared to unmanaged stands, or those thought to need 3-10 years of pre-harvest treatments before the overstory is removed.

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Table 1. Pretreatment density and basal area measurements of the major tree species present at the study area near Bellamy, AL.

Species	Trees ha^{-1}	Basal Area (m^2 ha^{-1})
Liquidambar styraciflua	38.6	6.41
Quercus shumardii	10.2	4.36
Carya spp.	47.4	3.73
Q. nigra	14.3	3.24
Q. pagodifolia	12.0	1.59
Ulmus spp.	18.1	1.08
Other *Quercus* spp. [1]	9.5	1.83
Other overstory tree spp. [2]	2.9	0.25
Subcanopy tree spp. [3]	17.4	0.87

[1] Other *Quercus* species include: *Q. rubra*, *Q. michauxii*, and *Q. alba*.

[2] Other overstory tree species include: *Fagus grandifolia*, *Acer rubrum*, and *Celtis laevigata*

[3] Subcanopy tree species include: *Halesia diptera*, *Carpinus caroliniana*, *Morus rubra*, *Ilex decidua*, *Asimina triloba*, and *Ilex opaca*.

Table 2. Oak, commercial, and non-commercial species groups present at the study site area Bellamy, AL.

Oak species group	*Quercus alba* *Q. michauxii* *Q. nigra* *Q. pagodifolia* *Q. rubra* *Q. shumardii*
Commercial species group (not including oak)	*Celtis laevigata* *Fraxinus pennsylvanica* *Liquidambar styraciflua*
Non-commercial species group	*Acer rubrum* *A. negundo* *Asimina triloba* *Carpinus caroliniana* *Carya* spp. *Cercis canadensis* *Diospyros virginiana* *Fagus grandifolia* *Halesia diptera* *Ilex decidua* *Morus rubra* *Nyssa sylvatica* *Ulmus* spp.

Table 3. Stocking[1], average height, and density of oak, commercial, and non-commercial species groups over time at the study area near Bellamy, AL.

	2000[2] (pre-treatment)	2001 (post-treatment)	2002 (post-harvest)
Oak species group			
Stocking %	69.7	59.4	95.8
Avg. height (cm)	9.25	10.26	13.71
Density by height class (stems ha^{-1})			
0-15 cm	71798	46675	18394
15-30 cm	85112	75092	36516
30-90 cm	33084	35691	57562
> 90 cm, up to 3.8 cm dbh	961	1648	1097
Commercial species group			
Stocking %	38.3	13.6	36.6
Avg. height (cm)	14.76	9.76	18.34
Density by height class (stems ha^{-1})			
0-15 cm	18671	3706	1509
15-30 cm	31574	8100	5354
30-90 cm	24023	9061	6177
> 90 cm, up to 3.8 cm dbh	6177	3980	2058
Non-commercial species group			
Stocking %	90.1	79.3	61.6
Avg. height (cm)	13.97	15.06	15.10
Density by height class (stems ha^{-1})			
0-15 cm	118060	64795	3293
15-30 cm	166794	96231	3432
30-90 cm	103783	75504	11806
90 cm, up to 3.8 cm dbh	30887	21826	1509

[1] Stocking is based on a species' presence or absence in seedling inventory plots
[2] Reported values are the result of combining data from all three treatments: control, understory reduction, and understory reduction plus vine treatment

Table 4. Stocking[1] and percent cover of Smilax, Vitis, Arundinaria, and Berchemia over time at the study area near Bellamy, AL.

	2000 (Pre-treatment)			2001 (Post-treatment)			2002 (Post-harvest)		
	C[2]	UR	URV	C	UR	URV	C	UR	URV
Smilax spp.									
Stocking	74.7	72.3	77.5	71.1	64.4	63.3	52.8	25.0	47.2
% Cover	7.1	7.4	7.1	7.9	7.1	7.3	10.5	7.4	9.7
Vitis spp.									
Stocking	62.8	59.4	58.3	53.9	57.8	56.1	38.9	30.6	36.1
% Cover	10.5	11.6	12.0	13.3	12.6	11.9	18.0	7.6	9.1
Arundinaria spp.									
Stocking	37.2	51.9	60.8	41.4	51.4	63.3	57.0	62.5	61.1
% Cover	14.3	17.1	20.3	15.6	16.0	22.6	8.5	11.4	11.4
Berchemia spp.									
Stocking	27.5	18.9	29.7	26.7	25.8	26.7	50.0	37.5	66.7
% Cover	5.9	5.4	5.4	5.0	5.1	5.8	14.1	10.6	11.1

[1] Stocking is based on a species' presence or absence in seedling inventory plots
[2] C = control, UR = understory reduction, and URV = understory reduction plus vine treatment

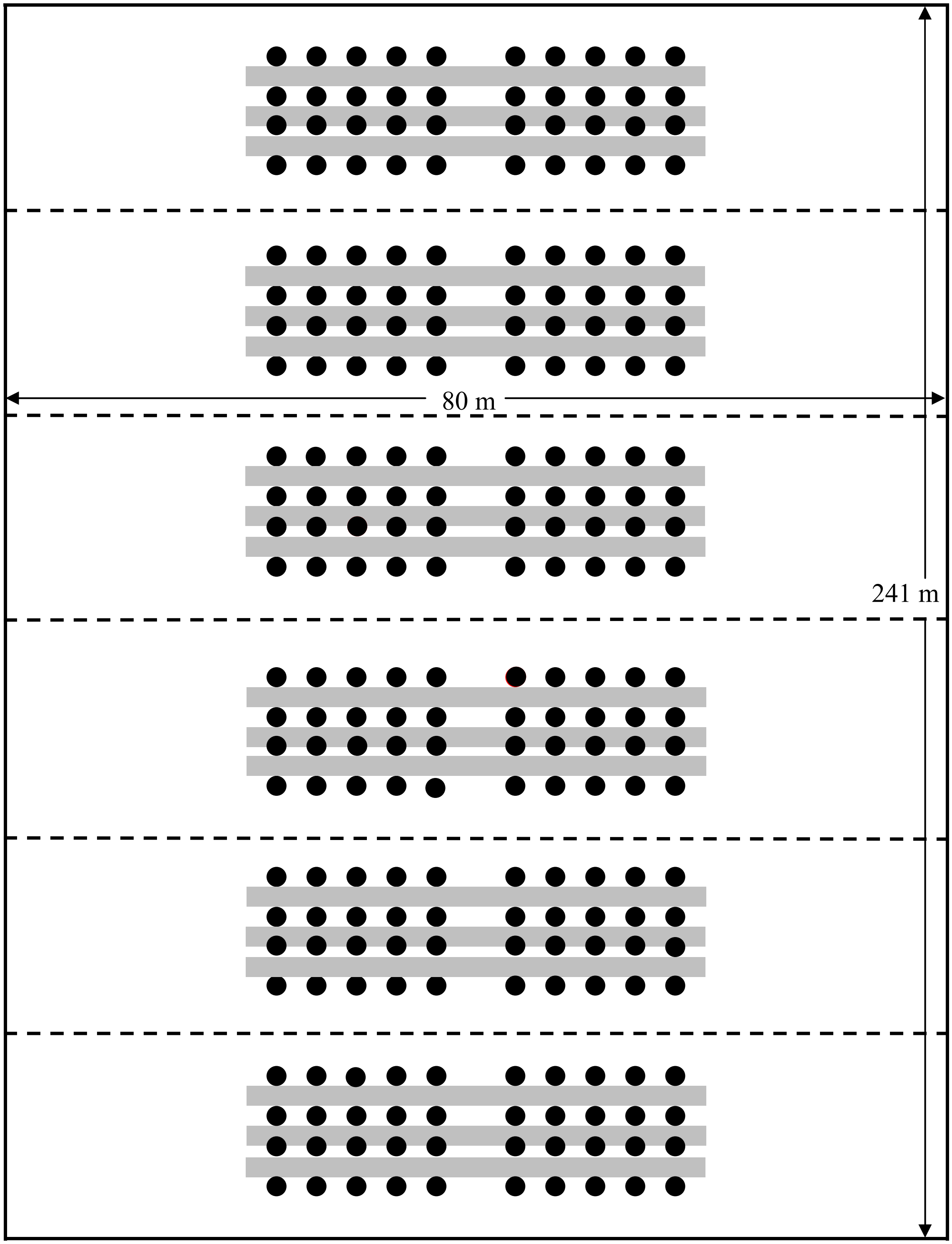

Figure 1. Diagram of a 2.5 ha research area. Dashed lines separate treatment areas, gray bars are reproduction survey strips, and black circles are underplanting sites for Nuttall oak seedlings.

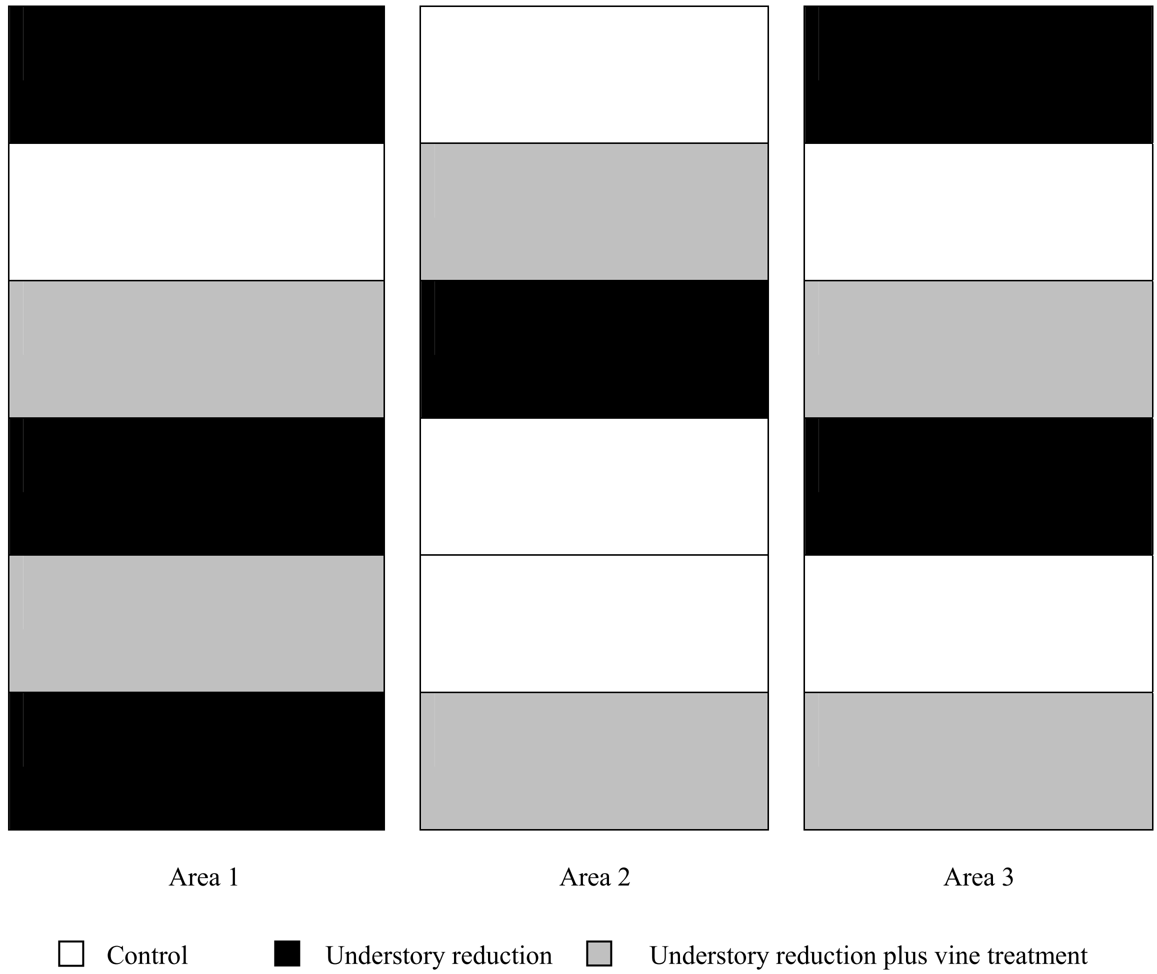

Figure 2. Completely randomized treatment diagram for the three 2.5 ha research areas at the study site near Bellamy, AL.

III. EFFECT OF ANIMAL BROWSE PROTECTION AND FERTILIZER APPLICATION ON THE ESTABLISHMENT OF PLANTED NUTTALL OAK SEEDLINGS

ABSTRACT

For establishment to be successful, planted oak must rise above vegetative competition and browse level. A three year study was established in 2000 on a cutover bottomland hardwood forest in west Alabama to examine the influences of seedling browse protection and fertilizer use on growth of Nuttall oak (*Quercus nuttallii* Palm.) seedlings. The treatments included: control, 1.2 m tall wire tree shelter, and 1.2 m tall plastic tree shelter. Fertilizer (20-10-5) was applied to one-half of all seedlings at planting. Competing vegetation was controlled around all seedlings with mulch mats and herbicide. Fertilization did not affect height growth or successful establishment after 3 years. Four percent of protected seedlings (plastic and wire tree shelters combined) were browsed compared to 95% of control seedlings. After 3 years, plastic tree shelters were the most effective treatment for promoting height growth and successful seedling establishment of Nuttall oak seedlings (193 cm, 92.71% compared to 120 cm, 68.75% and 52 cm, 8.33% for wire tree shelter, and control seedlings, respectively). Animal browse protection is deemed essential for successful seedling establishment in southern

bottomland forests where deer density is high (density estimated at 27 km^{-2} in vicinity of study area).

INTRODUCTION

Highgrading in southern bottomland hardwood forests has reduced the proportion and quality of oak trees that currently stock them. Forests once dominated by quality oaks (*Quercus* spp.) are currently stocked with scattered individuals of species that are commercially less desirable and/or have poorer form than oaks that have been removed (Johnson 1993). As these forests mature and are harvested, the question of how to successfully regenerate the existing oak component or re-establish more desirable oak species becomes pertinent. This problem is not restricted to southern bottomland hardwood forests or to previously highgraded stands. Techniques for regenerating oak-dominated stands seem to be unable to maintain or increase the numbers of established oaks following a regeneration harvest. Experiments in both northern (Heiligmann et al. 1985, Hix and Lorimer 1991) and southern states (Johnson and Krinard 1983, Golden and Loewenstein 1991) suggest that silvicultural methods for securing oak reproduction after harvest are, at best, only moderately successful. In all cases, oak seedlings were abundant at the beginning of the first growing season; however, their small size and slow growth allowed faster growing shade intolerant species to quickly occupy the sites. As a result, young oaks were unable to successfully compete for available resources and most died by the end of the first growing season, seemingly as a direct result of competition. Although some progress has been made using prescribed fire to reduce competition to oak seedlings (Brose et al. 1999), fire is typically not considered a viable option in southern bottomland hardwood forests (Toole 1959).

Lorimer et al. (1994) reviewed several oak regeneration studies throughout the eastern United States and indicated that seedling germination did not appear to be the limiting factor in oak establishment. Rather, slow growth and poor seedling survival, even of advance reproduction were recognized as key problems. Similar results were found in southern floodplain forests (Golden and Loewenstein 1991). Slow early growth of the oaks is a fundamental issue, primarily because species such as *Rubus* spp., *Vitis* spp., *Smilax* spp., and *Arundinaria* spp. are quick to occupy the full-light conditions present following a regeneration harvest. Such species initially grow taller than oaks and, in many cases, are able to quickly create a dense canopy that covers oak reproduction. Oaks, however, are intolerant to only moderately tolerant of shade (and the associated water/nutrient limitations). Consequently, oak seedlings that are unable to penetrate this competition are likely to die during the first few growing seasons.

The initial inability of oak seedlings to grow rapidly in height not only makes them vulnerable to vegetative competition, but also to animal browse. Until seedlings are able to grow above 1.25 m, they are susceptible to browse pressure from white-tailed deer (*Odocoileus virginianus* Zimm.) and are a preferred browse species (Castleberry et al. 1999). Intense browsing has adversely affected commercially important tree species in other forest types leading to a less desirable species composition in terms of both commercial value and forage quality (Anderson and Loucks 1979, Tilghman 1989, Walters 1993).

Efforts to protect seedlings from browse damage led to the invention of plastic tree shelters (Tulley 1985). These translucent tree shelters were approximately 1.2 m tall, allowed some light penetration, provided seedlings with a favorable microclimate, and protection from herbivory (Manchester et al. 1988). Research in Michigan has shown that tree shelters increased oak seedling survival and early height growth (Lantagne et al.

1990); comparable tests in North Carolina, Pennsylvania, and Connecticut confirmed these results (Manchester et al. 1988, Walters 1993, Ward et al. 2000). In the South, the effectiveness of tree shelters with planted oak has been investigated in urban environments (Jones et al. 1996, West et al. 1999) and on abandoned agricultural fields (Schweitzer et al. 1999) with excellent success. Survival and growth of bottomland oaks have been enhanced on cutover upland/bottomland transition zones in eastern Alabama (Dubois et al. 2000), but we are unaware of any published reports regarding the effectiveness of tree shelters on the establishment of bottomland oak species on recently harvested southern bottomland forests.

It is increasingly evident in areas densely populated with herbivores that some measure of protection is essential for desirable species to develop after a regeneration harvest. Wire tree shelters should be as effective as plastic tree shelters in protecting seedlings from browse, but may not provide the added benefit of stimulating height growth. An examination of wire tree shelters along side of plastic tree shelters will allow the quantification of any growth stimulation provided by plastic tree shelters. Another possibility for stimulating height growth in newly planted oak seedlings may be to apply fertilizer. The addition of essential nutrients, particularly in conjunction with vegetation control to allow these nutrients to get to the target plants, may provide seedlings with an initial increase in vertical growth that enables them to rise above both browse level and competing vegetation.

This study was designed to test the relative efficacy of various types of browse protection and growth stimulation on seedling establishment success in a southern bottomland hardwood forest. Specifically we examined differences in seedling survival, growth, and successful establishment among protection devices with or without a fertilizer application at the time of planting.

METHODS

Study Site

This study was conducted in a bottomland, mixed hardwood community adjacent to the Black Warrior River in Greene County, approximately 15 km north of Demopolis, Alabama, USA. The study site is located at approximately 32.5° N, 87.5° W and established in a forest that was clearcut and windrowed in the fall of 1999. Soils are of the Leaf-Angie association and consist mainly of poorly drained to moderately well drained, nearly level soils on broad stream terraces (USDA Soil Conservation Service, 1971). Average annual rainfall is 142 cm, and the average daily temperature ranges from 11°C to 24°C (Southern Regional Climate Center, 2004)

Experimental Design and Treatments

The study was set up as a completely randomized design with 324 seedlings receiving one of six treatments. Bareroot 1-0 Nuttall oak (Q. *nuttallii* Palm.) seedlings were hand planted in February 2000 in holes (approximately 50 cm deep) made using a portable gas-powered auger with a 15 cm bit. There were 13 rows planted on a 3 x 6 m spacing, with 24 or 25 seedlings per row. Three browse protection treatments were: control – no browse protection, 1.2 m tall plastic tree shelter, and 1.2 m tall wire tree shelter. Two 10 gram slow release fertilizer tablets (20-10-5 N, P, K) were placed in planting holes for one-half of all seedlings in each protection treatment.

Following planting, tree shelters (Tubex™ polyethylene tree shelters 10 cm x 1.2 m, Treessential Company, Saint Paul, MN) were placed over one-third (108) of the seedlings. Wire tree shelters approximately 30 cm in diameter and 1.2 m tall were fabricated from 5 cm by 10 cm welded wire fencing (14 gauge) and placed over one-third (108) of the seedlings. The remaining one-third (108) of the seedlings served as controls.

The effect of vegetative competition on seedlings was not a focus of this study, therefore, plant competition was removed. Black plastic mulch mats (approximately 1 m^2) were placed around each seedling to suppress competing vegetation. During the spring, mid- and late-summer of the first growing season, herbaceous and woody competition were chemically treated across the entire study area. The spring herbicide treatment consisted of a 4% (by volume) solution of RoundUp Pro™ (1.6 liters ha^{-1}). The herbicide effectively controlled most competing vegetation. However, it had little effect on hickories (*Carya* spp.), greenbrier (*Smilax rotundifolia*), and trumpet creeper (*Campsis radicans*). Subsequent applications were amended with 0.5% (by volume) of a surfactant (Timberland 90™). The herbicide solution was applied again in late spring and mid-summer during the second growing season. No evidence of herbicide damage was noted on planted seedlings following herbicide treatments.

Measurements

In February 2000, and at the end of each of the first three growing seasons in November of 2000, 2001, and 2003, survival, a categorical measure of animal browse, and seedling height were recorded. For the first two growing seasons, seedling groundline diameter (GLD) was measured at 2.5 cm above the groundline. Third year measurements of GLD could not be obtained because branching made it impossible to move the tree shelters without damaging the seedlings or destroying the protection devices. Browse injury was categorized as: 0 = no browse damage; 1 = slight browse damage – some side browse; 2 = moderate browse damage – side and terminal buds removed, 2-3 resulting forks; and 3 = extensive browse – side and terminal buds removed, 4+ forks.

Statistical Analysis

Analysis of variance (ANOVA) was used to examine treatment effects on seedling three-year height growth and two-year groundline diameter growth. Statistical contrasts were used to examine seedling growth differences among seedling protection devices and fertilizer application (Table 1). Effects of browse protection type and fertilizer use on seedling survival and establishment success were assessed using Chi-square criteria in logistic regression analyses.

RESULTS

Survival

Of the 324 Nuttall oak seedlings planted for this experiment in spring 2000, 304 (93.8%) were still alive following three growing seasons. There were no significant differences in survival among the protection/fertilization treatments. However, 55% of the seedlings that died were from the control group, 25% and 20% from the plastic tree shelter or wire tree shelter protection groups, respectively.

Seedling Height Growth

When planted, Nuttall oak seedling height averaged 29.8 cm. Seedlings that were fertilized and those protected from browse in general exhibited more height growth than seedlings in the control group all three years of the study (Table 2). Trees grown in plastic tree shelters were significantly taller than those in wire tree shelters (Tables 1 and 2). After three growing seasons, height growth for the control seedlings (51.9 cm) was 42.6% and 73.6% less than those in wire tree shelters (122.4 cm) and plastic tree shelters (192.9 cm) respectively (Table 2).

Across all tree protection treatments, fertilized seedlings grew an average of 131.9 cm compared to 115.4 cm for those unfertilized (Table 2). There were no statistically significant interactions between seedling protection type and fertilizer use on seedling height growth after three growing seasons. Seedlings that were either fertilized or enclosed in plastic tree shelters were significantly taller than unfertilized or those in the wire tree shelter or control groups (Tables 1 and 2). Unfertilized seedlings in plastic tree shelters added more than 3 times the height increment of fertilized seedlings in the control group and nearly twice the height increment of fertilized seedlings in the wire tree shelter group (data not shown).

Seedling Diameter Growth

When planted, Nuttall oak seedling average diameter was 4.35 mm. Seedlings that were fertilized and those protected from browse in general exhibited more diameter growth than seedlings in the control group all three years of the study (Table 2). After three growing seasons, diameter growth for the control seedlings was 26.8% and 36.3% less than those in wire tree shelters and plastic tree shelters, respectively. Trees in the wire tree shelters exhibited 12.9% less diameter growth than those seedlings growing in plastic tree shelters.

The application of fertilizer at the onset of the experiment improved seedling diameter growth (Table 2). Diameter growth was 15.5% less for the unfertilized seedlings compared to those fertilized at planting. There were no statistically significant interactions between seedling protection type and fertilizer use on seedling diameter growth.

Herbivory

After two growing seasons, the use of seedling protection significantly reduced browse injury compared to unprotected seedlings. Nearly 95% of control seedlings were injured by animal browse and no longer retain their terminal buds. Of the control seedlings, 28% suffered browse injury severe enough to cause extensive forking along the bole. Approximately 4% of seedlings protected by either wire tree shelters or plastic tree shelters were injured.

Seedling Establishment

Successful establishment was determined at the end of each growing season and was based on the seedling having grown to a height $\geq$1.25 m (Castleberry et al. 1999). Due to a lack of establishment within the other treatments, establishment success for the first growing season could only be tested within plastic tree shelters, comparing fertilized to unfertilized seedlings. Second-year analyses compared plastic tree shelters to wire tree shelters, and 3-year analyses were made among all treatment combinations. Examination of seedling establishment based on type of growth stimulation (either fertilizer use or plastic tree shelters) indicate that significantly more seedlings became established if they were fertilized or covered by plastic tree shelters than unfertilized seedlings in the control or wire tree shelter group (Table 3). After the first growing season, fertilized seedlings in plastic tree shelters exhibited significantly greater establishment success than unfertilized seedlings in plastic tree shelters. Results of second-year analyses reveal that seedlings in plastic tree shelters had significantly greater establishment success than seedlings in wire tree shelters. Ninety-three percent of seedlings in plastic tree shelters became established compared to 32% of seedlings in wire tree shelters. The use of fertilizer and the interaction between fertilizer and seedling protection devices were not statistically significant beyond the first growing season. Third year comparisons among all treatment combinations indicated that seedlings in the control group had considerably less establishment success (8%) compared to seedlings in either wire tree shelters (68%) or tree shelters (93%). A significantly greater proportion of the seedlings in the tree shelters grew to establishment height than those in wire tree shelters (Table 3).

DISCUSSION

The nearly complete vegetation control at the planting site may have affected seedling survival rates across the study. Our use of plastic mulch mats around each seedling in conjunction with multiple herbicide applications resulted in nearly 94%

survival across all treatments after three growing seasons. In this study there were no differences in mortality among the different protection devices or by fertilizer use. Similar results were reported by Dubois et al. (2000) in a two-year study in eastern Alabama examining the effects of tree shelters and weed control on *Q. pagoda* Raf. However, other studies involving the use of tree shelters have reported high rates of mortality (Manchester et al. 1988, Jones et al. 1996, West et al. 1999), especially for control seedlings when compared with those planted in tree shelters.

After three growing seasons, seedlings enclosed in plastic tree shelters had the greatest height and diameter growth. These results agree with other studies examining plastic tree shelters (Manchester et al. 1988, Schweitzer et al.1999, West et al. 1999, Dubois et al. 2000). It is generally accepted that height growth is accelerated by plastic tree shelters. Effects regarding diameter growth are mixed and seem to be dependant on species and age (West et al. 1999).

The one-time fertilizer application at the onset of this study enhanced seedling height growth after the first growing season, but the effect diminished with time. Although growth attributable to fertilizer application is modest, any cultural treatment that enhances seedling height growth should be considered if it has the potential to increase the proportion of successfully established seedlings.

Unprotected oak seedlings experienced extensive animal browsing irrespective of fertilizer use (95% of control versus 4% of protected seedlings). This is consistent with a study of planted cherrybark oak where approximately 60% of unprotected seedlings were browsed compared with < 10% of seedlings growing in shelters (Dubois et al. 2000). Some seedlings in the current study were browsed so severely that their height decreased during sequential measurement periods. Not only were seedlings in the control group radically shorter than those surrounded by protective devices, their form had also become less desirable. Seedlings in tree shelters were much taller, straighter, and typically maintained a single central stem as opposed to the short, bushy stature of unprotected seedlings (personal observation). The intense browse pressure observed on this site may be attributed to high deer density ($\geq$ 27 deer km^{-2}) and exacerbated by the fact that this study occupied a small area of a larger clearcut. It has been noted that ease of foraging due to spatially concentrated resources in clearcuts may explain their high use by deer in the spring and summer months in north Georgia (Ford et al. 1994). If deer were attracted to the clearcut for browsing activities then, due to the nearly complete competition control, the unprotected oak seedlings may have been more apparent to deer and therefore more susceptible to browsing. However, Dubois et al. (2000) found no statistically significant difference in browse pressure among unprotected seedlings with and without vegetation control, so it may be possible that the vegetation control applied in this study did not affect browse pressure.

Our results demonstrate that seedling protection and fertilizer enhance establishment and early growth of Nuttall oak following clearcutting. However, growth benefits must be cost effective because initial planting costs, including cultural treatments, will limit the number of seedlings a forest landowner will plant. To evaluate this issue, we estimated planting costs for oaks after a regeneration harvest. The following assumptions (using actual 2000 costs inflated to 2004 real prices) were used to determine the price per planted seedling.

Cost per seedling

1-0 oak seedling	$0.65
Planting labor	$0.19
Wire tree shelter	$2.45
Plastic tree shelter	$2.65
Bamboo stake	$0.20
Fertilizer tablets	$0.10

The cost of planting a seedling in the control group is $0.84 (seedling cost plus planting labor) and the cost of a planted seedling using a plastic tree shelter is $3.69 (seedling cost, labor, stake, and plastic tree shelter). Seedlings in wire tree shelters were only marginally cheaper than those in plastic tree shelters at $3.49 (seedling cost, labor, stake, and wire), but were more labor intensive to install. The cost of applying fertilizer to any seedling was an additional $0.10 per planting hole. The cost of vegetation control treatments (mulch mats and herbicide application) is not included in the cost estimates for several reasons. Operationally, because total vegetation control is rarely practiced, therefore, inclusion of these costs would inflate estimates. Further, operational costs vary greatly from research costs largely due to economies of scale depending on the total area treated. Finally, even if intensive vegetation control were used, application would cease upon seedling establishment. As complete control was maintained for all seedlings throughout the entire study period regardless of establishment status, a reasonable cost estimate per seedling by treatment is not possible.

Based upon these assumptions, a cost per established seedling was determined by multiplying the reciprocal proportion of the number of established seedlings with the cost per planted seedling (Table 3). For example, if 100 seedlings were planted in plastic tree shelters at a cost of \$3.69 per seedling and 90 of 100 seedlings became established, the cost per established seedling would be \$3.69 x 100/90, or \$4.10. Our data are similar to Dubois et al. (2000) who estimate establishment costs at \$4.80. It should be noted that the costs presented are for the period of establishment only; there may be additional expenses associated with ongoing maintenance of tree shelters (see Schuler and Miller 1996). In particular, tree shelter removal will be required with use of the wire type shelter and may be necessary with the plastic shelters if they do not photo degrade over time as they are designed to do. Wire shelters may be reused, thus greatly reducing costs associated with subsequent installations.

CONCLUSIONS

Although planting costs are higher, after three growing seasons the cost per established seedling (≥1.25 m tall) is about \$4.00 for plastic tree shelters, \$5.15 for wire tree shelters, and \$10.50 for seedlings left unprotected. The use of fertilizer, may provide an initial increase in seedling height and diameter growth, thus reducing time to establishment. Even though this growth stimulation is a short term effect, at a cost of only \$0.10 per seedling, if initial height gains enable seedlings to rise above the 1.25 m browse level (Castleberry et al. 1999) it is of little consequence if these effects are lost over time. It should be noted that cost estimates per established seedling are based on seedling grown with total competition control. The cost of such control will need to be factored into establishment costs. If these measures are not taken, the costs per established seedling will likely increase due to competition induced mortality. This increased mortality and cost will affect the control treatment at a proportionately higher rate, because of their relatively slow rate of growth in comparison to the tree shelter treatments. Our data indicate that the use of browse protection is necessary in southern bottomland forests, and that the type of device used can greatly enhance seedling growth rates. Plastic tree shelters not only aid in the rapid establishment of oak seedlings, but the resulting stem form is superior to open-grown, or seedlings in wire tree shelters. If landowners want to grow high-quality oak seedlings rapidly above browse level and competing vegetation, plastic tree shelters and fertilizer should be used. In the longer-term they are highly cost-effective.

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Table 1. Contrasts, their associated codes and Chi-square values for total seedling height growth by year, protection treatment, and fertilizer use (F = fertilized, NF = not fertilized).

Contrast	Control		Wire Tree shelter		Plastic Tree Shelter		Year		
	F	NF	F	NF	F	NF	1	2	3
Protection v. No Protection	-2	-2	1	1	1	1	P < 0.0001	P < 0.0001	P < 0.0001
Plastic vs. Wire Tree shelter	0	0	1	1	-1	-1	P < 0.0001	P < 0.0001	P < 0.0001
Growth Stimulant v. No Stimulant	1	-2	1	-2	1	1	P < 0.0001	P < 0.0001	P < 0.0001
Plastic Tree Shelters v. Fertilizer	1	0	1	0	0	-2	P < 0.0001	P < 0.0001	P < 0.0001

Table 2. Annual height growth increment (cm) and groundline diameter increment (mm) of planted Nuttall oak seedlings by fertilizer use and protection type.[1]

	Growth by fertilizer use[2]		Growth by protection type[2]		
	No	Yes	Control	Wire Tree Shelter	Plastic Tree Shelter
Year 1					
Height	18.9 b	26.5 a	6.9 b	11.8 b	49.8 a
GLD	3.5 a	4.4 a	3.3 b	3.8 b	4.7 a
Year 2					
Height	67.9 a	71.2 a	21.7 c	71.7 b	116.4 a
GLD	9.6 b	11.1 a	7.6 c	11.1 b	12.4 a
Year 3					
Height	28.6 a	34.2 a	23.3 b	38.9 a	26.7 b
Total					
Height	115.4 b	131.9 a	51.9 c	122.4 b	192.9 a
GLD[3]	13.1 b	15.5 a	10.9 c	14.9 b	17.1 a

[1] Growth increment does not include initial seedling height or groundline diameter.

[2] Means followed by the same letter, within the same row, and within either fertilizer use or protection type are not significantly different ($\alpha = 0.05$) using Duncan's New Multiple Range Test.

[3]·Total increment for groundline diameter is for two years.

Table 3 –Percentage of Nuttall oak seedlings successfully established (≥ 1.25 m tall) and cost per established seedling in year 3 [1] by protection type and fertilizer use.

Protection Type	Fertilizer	Year 1[2]	Year 2	Year 3
Control	No	0.0 %	0.0 %	8.3 % c $10.08
	Yes	0.0 %	1.9 %	8.3 % c $11.28
Wire Tree Shelter	No	0.0 %	20.4 % b	64.6 % b $5.40
	Yes	0.0 %	38.9 % b	72.9 % b $4.92
Plastic Tree Shelter	No	7.4 % b	92.6 % a	93.8 % a $3.94
	Yes	18.8 % a	94.4 % a	91.7 % a $4.13

[1] Cost is calculated by multiplying the reciprocal proportion of the number of established seedlings by the cost of planting a seedling in the same group.

[2] Means followed by the same letter within the same column are not significantly different ($\alpha = 0.05$) using Duncan's New Multiple Range Test.

IV. SUMMARY

This study examined the impacts of pre-harvest treatments applied one year in advance of overstory removal to determine if this is a sufficient amount of time to establish natural oak reproduction when there is a good acorn crop, or if this is enough time to allow artificially regenerated seedlings to overcome transplant shock such that they can be competitive once the overstory is removed. Shelterwood prescriptions typically indicate the need for treatment application between 3-10 years before overstory is removed. This not only requires yearly monitoring, but the stature of natural oak reproduction is difficult and costly to assess. Both of our pre-harvest treatments improved the stocking of oak and commercial species in a year when there was a good acorn crop. Although the vine treatment was not successful in reducing their stocking, it appears that it was partially effective and may allow natural oak reproduction the opportunity to establish a well-developed root system more quickly, making them more competitive.

If there is no acorn crop, or it is less than optimal, typical prescriptions for underplanting oak typically call for them to be planted several years prior to overstory removal to allow them time to overcome transplant shock and establish a good root system. Underplanting one year in advance of overstory removal appears to be an adequate amount of time for Nuttall oak to overcome transplant shock and is a feasible option for land managers. Although many of the planted seedlings were unable to be located after harvest, this still is an excellent way to supplement natural oak regeneration and improve the spatial distribution of stems, especially when harvest occurs during a good seed year.

When there is no acorn crop or seed source, or if pre-harvest planning is not a feasible option, we examined the efficacy of post-harvest planting with site preparation and the utilization of seedling protection. The use of plastic tree shelters and fertilizer significantly reduced the amount and intensity of animal browse and greatly improved seedling height growth and stem form in areas densely populated with herbivores. Although planting costs are higher, after three growing seasons the cost per established seedling (≥m tall) is 25% and 250% greater for wire tree shelters and unprotected seedlings, respectively, compared to those in plastic tree shelters. Growth attributable to fertilizer application was modest but any cultural treatment that enhances seedling height growth should be considered if it can increase the numbers of successfully established seedlings.

The findings of this study indicate that preharvest treatments to increase understory light levels or decrease vine abundance prior to overstory removal is essential for increasing the stocking and competitive stature of naturally regenerated oak seedlings. The underplanting of oak seedlings prior to overstory removal is also a viable option to increase the stocking and/or control the spatial distribution of desirable stems. Where pre-harvest planning is not an option, planted seedlings should be protected using plastic tree shelters and fertilizer should be used. Seedlings become established more rapidly, and their resulting form is far superior to those open-grown or in wire tree shelters.

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