Hardwood Regeneration

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UPLAND VS. BOTTOMLAND SEED SOURCES OF CHERRYBARK OAK

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Abstract—The influence of seed sources (upland vs. bottomland) on first-year height increment, groundline diameter increment, leaf number, seedling emergence, and survival percentages of cherrybark oak (*Quercus pagoda Raf.*) was investigated on a bottomland, a terrace, and an upland planting site. Cherrybark oak acorns were collected from open pollinated trees at nine bottomland and eight upland stands across an east-west transect in central Mississippi. The acorns were sown on a bottomland site and a terrace site in Carroll County, and on an upland site in Winston County in central Mississippi. The soils at the planting sites are classified as Oaklimeter silt loam (coarse-silty, mixed, thermic Fluvaquentic Dystrochrepts), Loring silt loam (fine-silty, mixed, thermic Typic Fragiudalfs), and Maben fine sandy loam (fine, mixed, thermic Ultic Hapludalfs), respectively.

First-year results showed that upland and bottomland seed sources did not differ for seedling emergence, survival, height increment, groundline diameter increment, and leaf number. However, large planting site and stand variations in some measured traits were detected. Planting sites varied with respect to seedling emergence, survival, height, ground line diameter, leaf number, and leaf number per centimeter of height. The terrace planting site generally was best. Stands (acorn collection sites) varied significantly for laboratory germination, height increment, and leaf number. Three of the highest germination values came from the Upper Coastal Plain and Blackland Prairie Soil Resource Areas of Mississippi. However, acorns coming from the stands in the Mississippi River Delta resulted in the poorest value for speed and completeness of germination. Acorns from a stand in the Upper Thick Loess Soil Resource Area of Mississippi had the largest height growth, and acorns from a stand in the Upper Coastal Plain Soil Resource Area of Mississippi demonstrated the highest leaf number. There were only small changes between height rank and leaf number rank of stands. Tallest first-year heights were generally associated with the greatest number of leaves. There was no pattern of change among stands from east to west for the traits of height and leaf number, except germination value. First-year results suggest that topographic position of seed sources is not important to regeneration success.

INTRODUCTION

Cherrybark oak (*Quercus pagoda Raf.*) is one of the most valuable red oaks in the lower Mississippi River valley because of its fast growth, clear bole, and value for wildlife. The tree occurs naturally from eastern Texas north along the Mississippi River to southern Illinois and Indiana, and east to southern Virginia (Fowells 1965). It occurs on a range of sites from dry-mesic uplands to floodplains.

Even though cherrybark oak genetic investigations have been conducted in recent decades (Dicke and Toliver 1987, Greene and others 1991, Randall 1973), unknown seed source is still a prevailing concern for private individuals and seed dealers. Most acorns for seedling production and direct seeding are collected from upland sites, although most of the artificial regeneration is being done on floodplain sites in the South. This could pose a problem for survival and growth of the seedlings.

The objectives of this study were to investigate factors affecting survival and growth of acorns of cherrybark oak including: (1) upland and bottomland seed sources, (2) variation among topographical position of planting sites, and (3) variation among stands from which acorns were collected.

MATERIALS AND METHODS

Planting Stock

Four to 10 cherrybark oak trees from natural stands on nine bottomland and 8 upland sites were chosen for acorn collection on an east-west transect across central Mississippi (fig. 1). "Bottomland (B)" and "upland (U)" sites represent two topographic positions. Bottomland sites are in the floodplain and subject to brief periods of flooding each year. Acorns were collected from those open pollinated trees in the fall of 1995, and were immersed in water to remove empty or defective "floaters." The "full" acorns collected from trees at one site were mixed in equal numbers from each tree to provide a stand mix. These acorns were placed in sealed, zip-lock plastic bags, and stored in a cooler at 3C until the first week of March 1996, when they were manually sown in paired seed spots. The depth of seed placement was about 5 centimeters. A total of 8,160 acorns were sown at three planting locations, excluding borders.

Test Locations

Trials were planted on a bottomland site and on two upland sites, one of which was a terrace site, in central Mississippi (fig. 1). The bottomland and terrace planting sites were located in Carroll County, MS (latitude: 33°18' N, longitude: 89°40' W, T.17 N and R.6 E). The upland planting site was situated in Winston County, MS (latitude: 33°15' N, longitude: 89°06' W, T.16 N and R.12 E). The planting sites in Carroll County were old fields. The planting site in Winston County was an opening in a pine-hardwood forest on a south slope. The soils at the planting sites were classified as Oaklimeter silt loam, moderately well drained (coarse-silty, mixed, thermic fluvaquentic Dystrochrepts); Loring silt loam, moderately well drained (fine-silty, mixed, thermic Typic Fragiudalfs) (USDA Soil Conservation

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Service 1990), and Maben fine sandy loam, well drained (fine, mixed, thermic Ultic Hapludalfs) (USDA Soil Conservation Service, unpublished), respectively.

Experimental Design

A randomized complete block design was used. Every planting site had four blocks. In a block there were 17 adjacent plots representing stands. The acorns from each stand were sown in 2 rows with 10 planting positions in each row in a plot. In other words, 20 seeded positions were installed in a plot. There were two acorns planted at each planting position, and positions were spaced at 3 by 3 meters. Two border rows were installed around each block. Blocks were randomly assigned in a planting location, and then plots (acorn sources of stands) were randomly assigned within a block. All effects in the population model were considered random because the entire population was of interest. Inference can be made from this experiment for the entire population of cherrybark oak.

Weed Control

Weeds were controlled in the first year by mowing and disking between trees and with direct spray application of herbicide. After sowing (but just before seedling emergence) a tank mixture of Gramoxone® and Goal® was sprayed in a 1.5-meter band for every planting row to control the early emergent weed species. The dosage was 56.2 milliliters Goal®/liter (5.8 liters/hectare) and 22.43 milliliters Gramoxone Extra®/liter (2.3 liters/hectare). After seedlings emerged, Fusilade® 2000 was sprayed two times at 30-day intervals as 12 milliliters/liter (1.2 liters/hectare), including 3 milliliters surfactant/liter. In addition, glyphosate was applied two times as a directed spray on weed species at the dosage of 22.45 milliliters/liter (5.9 liters/hectare) by putting a 45-centimeter PVC pipe around the seedlings. A piece of aluminum foil was placed on the top of pipes to prevent drift of glyphosate onto the oak seedlings.

Data Collection and Analysis

Traits measured on every seedling were height, groundline diameter, leaf number per seedling, seedling emergence, and survival. Height and groundline diameter were measured in millimeters. In the case of multiple stems, the height of the tallest stem was recorded. Seedling emergence counts were made on June 15, July 15, early August, and early September 1996. When the seedling had two leaves, it was scored as emerged. Where two seedlings survived at a flagged position, one of them was randomly chosen and the other was removed in October 1996. All final measurements were taken in the first week of October 1996. Survival was determined from this final measurement.

Differences between seed sources and among stands were evaluated by analysis of variance on a plot-mean basis. A format of the analysis of variance table is shown in table 1. A Satterthwaite-F (pseudo-F) test (Steel and Torrie 1980) was used for the "planting sites and topographic positions of stands" sources of variation. All analyses were performed using SAS statistical procedures (SAS Institute Inc. 1988).

Table 1—Format of analysis of variance for cherrybark oak seed source trails on two upland sites and a bottomland site

Source of variation	df	Expected (MS)
Total (corrected)	203	
Planting sites (L)	2	$a^2_{SB(L)} + 17\alpha^2_{B(L)} + 4\alpha^2_{SL} + 68\alpha^2_{L}$
Blocks within L. (B/L)	9	$\alpha^2_{SB(L)} + 17\alpha^2_{B(L)}$
Stands (S)	16	$\alpha^2_{SB(L)} + 4\alpha^2_{SL} + 12\alpha^2_{S}$
Topographic positions of stands (T)	1	$\alpha^2_{SB(L)} + 4\alpha^2_{SL(T)} + 12\alpha^2_{S(T)} + 68\alpha^2_{TL} + 204\alpha^2_{T}$
Stands within T.(S/T)	15	$\alpha^2_{SB(L)} + 4\alpha^2_{SL(T)} + 12\alpha^2_{S(T)}$
Stands * P. sites (S*L)	32	$\alpha^2_{SB(L)} + 4\alpha^2_{SL}$
T*L	2	$\alpha^2_{SB(L)} + 4\alpha^2_{SL(T)} + 68\alpha^2_{TL}$
S/T*L	30	$\alpha^2_{SB(L)} + 4\alpha^2_{SL(T)}$
S*B/L	144	$\alpha^2_{SB(L)}$

Laboratory Germination Test

The test was run at the Forestry Sciences Laboratory, Starkville, MS, which is maintained by the Southern Research Station of the USDA Forest Service. Germination of oak acorns was tested by the "cut and peel" method, as in standard testing procedures (AOSA 1978, Bonner 1984). Fifty acorns were used from each stand for the test, and the whole test was replicated four times. The acorns were cut in half and the pericarps were removed.

The germination test was accomplished in a germination chamber. Kimpak (cellulose paper wadding) was used as germination medium. Light was furnished for the 8-hour "day" portion of the cycle. Night and day temperatures in the cabinet were set on 20 °C and 30 °C, respectively. A 3-centimeter space was left between acorns on the Kimpak in labeled germination trays. An acorn was scored as germinated when plumule and root development were observed. The test was run until the last acorn germinated. Germination counts were made at the same time every day. Fungal infected and ungerminated acorns were also counted. Germination percentage and germination value (GV) were calculated. Czabator's formula was used to quantify the germination value of acorns from different stands (Czabator 1962).

RESULTS AND DISCUSSION

Upland vs. Bottomland

Results supported the null hypothesis that there was no difference between upland and bottomland seed sources for the measured traits in the first year (table 2). Therefore, the collection of acorns from upland sites for planting on

Table 2—Mean squares and F-test results for field emergence and laboratory germination, survival percentage, height, groundline diameter, leaf number, and leaf number per centimeter of height for 1-year-old cherrybark oaks; upland vs. bottomland seed sources

		Mean squares[a]						
Sources of variation	df	Field emerg	Lab. germ	Surv	Hght	Grnd line diam	Leaf #	Leaf # per cm height
Planting sites	2	23455**	—	9683**	23299**	18**	493**	0.7**
Blocks within P. sites	9	302.4**	—	325.3	4980.3	0.8*	16.9	0.1**
Topographic position of stands (Topo)	1	200.8	0.5	0.8	3847.5	0.2	11.4	0.03
Stands within Topo	15	293.4	394*	248.4	2736*	0.4	16.6**	0.02
P. sites * Topo	2	426.7	—	300.7	2406.8	0.1	0.1	0.004
P. sites* stands within Topo	30	185.0*	—	187.7	1351.0	0.2	5.0	0.03
Stands* blocks within P.sites	144	102.8	—	252.6	3017.6	0.4	10.8	0.03
Blocks	3	—	58.9	—	—	—	—	—
Stands * blocks	48	—	183.6	—	—	—	—	—

[a] Where,* indicates the calculated F was significant at the alpha = 0.05 level, and ** indicates the calculated F was significant at the alpha = 0.01 level.

bottomland sites should not cause any problem in seedling emergence, survival, and first-year growth of the seedlings. However, later problems as the stand develops cannot be predicted based on these first-year results.

Great genetic variation in species that occur naturally in disjunct populations can generally be expected (Zobel and Talbert 1984). A possible explanation for this lack of significant variation between upland and bottomland seed sources in close proximity to each other is that migration prevents the evolution of bottomland and upland ecotypes by natural selection. Similarly, Larsen (1963) found, in his investigation of the effects of water soaking on acorn germination of four southern oaks, that susceptibility to flooding injury was not significantly different between “dry site” species and “bottomland site” species. In contrast, results from a northern red oak study by Kubiske and Abrams (1992) clearly demonstrated that xeric and mesic seed sources showed ecotypic differences in leaf morphology, photosynthesis, and water relations during drought in the first year, even though seed sources came from neighboring sites in central Pennsylvania.

Variation Among Planting Sites

Significant variation was found among planting sites in mean field emergence, survival, height, groundline diameter, total leaf number, and leaf number per centimeter of height (table 2). Emergence was 55 percent at the terrace, 24 percent at the bottomland, and 22 percent at the upland planting site (table 3).

Lowest field emergence at the upland planting site might have been caused by consumption of acorns by small mammals and birds, although digging and other clear evidence of acorn destruction in the field were not observed. Munns (1921) has proposed that the moisture content of soil affects the germination of forest tree seeds. A fluctuation in water content on either side of what is called “the optimum range of soil moisture for germination” would cause a decrease in germination. Therefore, the poor field emergence at the upland and bottomland planting sites might have been caused by too little and too much soil moisture during a critical period of acorn germination. Some studies have reported that waterlogged soils inhibit oak germination (Briscoe 1961, Hosner 1957). In this study, the bottomland planting site was flooded several times from the nearby Big Black River in March through June 1996. This might have reduced the germination at the bottomland planting site. After the germination period, however, seedling survival percentages at the bottomland and terrace planting sites were very similar (even slightly higher on the bottomland site), and about 24 to 25 percent higher than seedling survival on the upland planting site (table 3). Dry soil conditions during the summer after acorn germination might be responsible for these results.

Table 3—Overall means of cherrybark oak of field emergence, survival, height, groundline diameter, and leaf number on the bottomland, terrace, and upland planting sites

Traits measured	Overall mean of P. sites			
	Bottomland	Terrace	Upland	Overall avg.
Field emergence (percent)	23.68	55.26	22.43	33.79
Survival (percent)	86.17	85.46	64.98	78.87
Height (mm)	175.54	185.38	150.43	170.44
Groundline diameter (mm)	2.82	3.12	2.10	2.68
Leaf number	12.63	14.48	9.28	12.15

Much has been written about the effects of flooding on acorn germination and seedling survival of cherrybark oak, but there is little on the effects of summer drought. Cherrybark oak seedlings are classified as intolerant to flooding (Hosner and Boyce 1962, McKnight and others 1980, Pezeshki and Chambers 1985). Under water saturated soil conditions, leaf moisture deficits apparently induced the early death of cherrybark oak seedlings due to reduced water uptake resulting from root mortality (Hosner and Boyce 1962). However, findings of Pezeshki and Chambers (1985) contradicted this. Water deficits did not result from flooding, based on the leaf xylem pressure potential measurements in cherrybark oak under controlled environmental conditions. Flooding causes stomatal closure, lower transpiration rates, and reduction in net photosynthetic rate in cherrybark oak (Pezishki and Chambers 1985). These factors might have contributed to failure on the bottomland planting site, because seedling height, groundline diameter, and leaf number were higher on the terrace planting site than the seedling means on the other two planting sites (table 3). The bottomland planting site was ranked second for the same traits. Hosner and Boyce (1962) reported that 60-day periods of saturated soil under controlled environmental conditions did not affect the height growth of cherrybark oak seedlings. Drought at the upland site seems a big problem. The lowest values of the measured traits at the upland planting site may indicate the importance of available water in the soil during the growing season.

Stand Variation

Significant variations were found among stand means averaged over the three planting sites for laboratory germination, height, and leaf number (table 2). Stands within topographic positions varied for mean germination value when germinated under controlled laboratory conditions (p=0.023) (table 2). This source of variation was not significant in the field tests, probably because of the planting site-by-stand-within-topographic-position interaction and because measurements were taken at long intervals.

The mean germination values of acorns of stands ranged from 88 (stand 9B) to 57 (stand 15B) in the laboratory test. Acorns from stand 9B had approximately 35 percent more germination speed and completeness than stand 15B. Stand differences of this magnitude could be important. Large gain for germination speed and completeness can be obtained from choosing the best stands for acorn collection.

While three of the highest germination values came from stands 9B and 13B (the Upper Coastal Plain Soil Resource Area of MS) and 10B (the Blackland Prairie Soil Resource Area of MS), which were bottomland stands, acorns of the two stands 3B and 15B from the Mississippi delta had the lowest germination values (fig. 2). There was a pattern of change among stands from east to west. Acorns from the two west stands (3B and 15B) demonstrated the poorest germination values. These two delta sources also slowly completed the germination process. Low germination values of acorns of those two stands might be due to selfing, because the stands are isolated from other cherrybark oak stands.

Pettry (1977) has said “Mississippi may be divided into ten major soil resource areas, each containing soils, topography, and climatic factors that make it distinct from the other land areas.” Those soil resource areas of Mississippi are Delta, Upper and Lower Thick Loess Areas, Upper and Lower Thin Loess Areas, Upper Coastal Plain, Lower Coastal Plain, Blackland Prairie, Interior and Coastal Flatwoods (fig. 1). Based on this division, the stands coming from the Upper Coastal Plain Soil Resource Area were above average for germination value (fig. 2).

The cause of different stand values for acorn germination in the laboratory study is not known. Possible reasons include kind of reserve food materials (such as fats and carbohydrates), different temperature requirements for germination, or differences in degree of dormancy. Kramer and Kozlowski (1979) attributed the seed dormancy of oaks to physiological embryo dormancy. Vogt (1974) in northern red oak found a decrease of an abscisic-acid-like germination inhibitor and the increase of a gibberellin-like germination promoter during stratification. In the germination of acorns of some stands this type of mechanism may have been involved.

After one growing season, significant variation among stands within topo positions occurred for height increment (p=0.049) (table 2). The mean height of seedlings of stands ranged from 139 to 194 millimeters in the field. Seedlings of stand 2U, located in the Upper Thick Loess Soil Resource Area, were the tallest (fig. 2). There was no pattern of change among stands from east to west for this trait. Other researchers also found significant differences among provenances in cherrybark oak (Dicke and Toliver 1987, Greene and others 1991, Randall 1973).

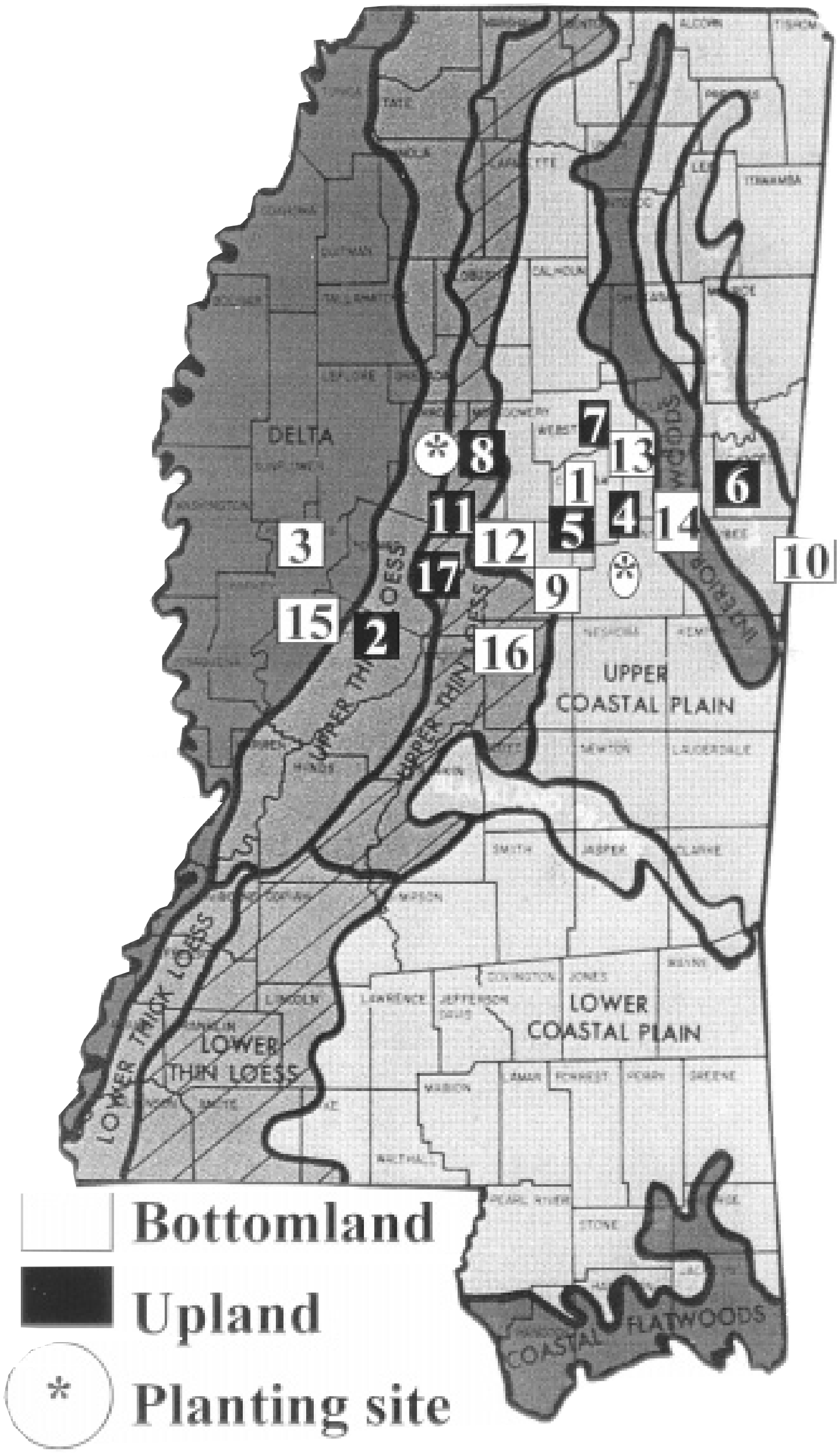

Figure 1—Acorn collection and planting sites in Mississippi (Pettry 1977).

Stands within topographic positions varied relative to mean leaf number (p=0.002) (table 2). The mean leaf number of seedlings of stands ranged from 14 (stand 4U) to 10 (stand 15B) in the field. There was no pattern of change among stands from east to west for leaf number of seedlings (fig. 2). Stand rankings for leaf number were similar to rankings for height. Although stands within topographic positions were significant for leaf number, the leaf number per centimeter of height was not significantly different (table 2). Taller seedlings had more leaves.

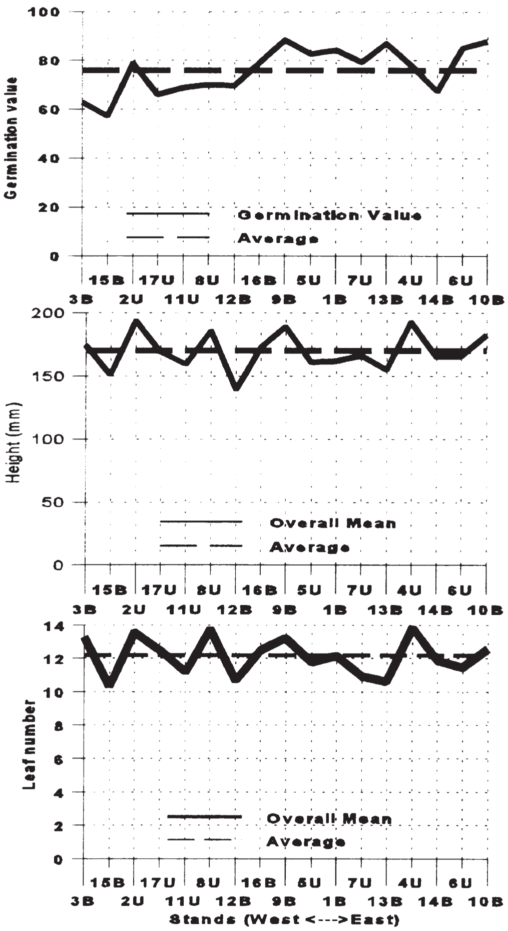

Figure 2—Mean germination value of acorns, mean height increment and leaf number of seedlings from 17 cherrybark oak stands across an east-west transect in central Mississippi.

McGee (1968) reported that there was a high correlation between seed source and number of leaves per seedling in northern red oak. He partially attributed this high correlation to the high number of multiple stems produced by one particular seed source.

Planting-Sites-by-Stands within Topographic Position Interaction

The only interaction between planting sites and stands within topographic positions was for mean percent field emergence (p=0.0043) (table 2). Stands 4U and 6U (fig. 1) ranked 15th and 17th at the bottomland planting site, 4th and 17th at the terrace planting site, and 2nd and 3rd at the upland planting site, respectively. Stands 1B and 12B ranked 2nd and 6th at the bottomland planting site, 11th and 16th at the terrace, and 16th and 17th at the upland planting site, respectively. The two upland stands moved to the high ranks as they changed bottomland to upland planting sites, while the two bottomland stands moved to the lowest ranks as they changed from bottomland to upland planting sites. These were the four extreme stands for rank changes and probably were responsible for the significant interaction. However, this pattern was not true for all stands from the same topographic position (topographic position by site was not significant). Therefore, no definitive conclusion can be drawn about matching stand origin with the topographic position of the planting site.

CONCLUSION

There was no significant variation between upland and bottomland seed sources. Acorns from upland and bottomland sites had similar first-year performance when planted on either type of site. However, large variation among planting sites occurred with respect to seedling emergence, survival, first-year height increment, first-year groundline diameter increment, and leaf number. The terrace planting site was generally best. The differences among planting sites may be due to moisture content of soils during germination and during the summer. There was variation among stands within the two topographic positions for laboratory germination, height increment, and leaf number. Acorns from the two delta stands had the lowest germination value. There was no pattern of change among stands from east to west for height and leaf number, except germination value of acorns. Much of the variability among stands was random with regard to location. Poor rank correlations among planting sites contributed to interactions between planting sites and stands within topographic positions for seedling emergence in the field. Some stands moved to the high ranks as they changed the planting site from bottomland to upland, while some stands moved to the lowest ranks as they changed the planting site from bottomland to upland. The results obtained in this study indicate that topographic position of stands where acorns were collected does not influence the first-year regeneration success. Planting-site selection and collection of acorns from healthy stands with a large cherrybark oak component (for good cross pollination) are probably more important for the success of reforestation.

ACKNOWLEDGMENT

Thanks are extended to Yonca Karagul for help during the project, Dr. Andrew W. Ezell for comments on weed competition control, and D. Ramsey Russell for help in selecting stands.

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REGENERATION EFFICIENCY OF BAREROOT OAK SEEDLINGS SUBJECTED TO VARIOUS NURSERY AND PLANTING TREATMENTS

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Abstract—Seedlings of cherrybark oak (*Quercus falcata* var. *pagodifolia* Ell.) and northern red oak *(Quercus rubra* L.) from five seedbed densities were outplanted using three root-handling treatments. Using a cost-over-benefit evaluation technique, the components of cost (seedling cost, seedling weight, and planting rate) and performance (survival, diameter, and height) were analyzed concurrently. In general, seedlings from low seedbed densities were lowest in cost, but those from high seedbed densities were highest in performance. The dug-hole method of planting was more costly to implement than the two compression methods of planting, yet it showed some improvement in seedling performance over the compression methods. The evaluation of regeneration efficiency indicated that the performance advantage gained from growing seedlings at low seedbed densities and planting them by the dug-hole method did not overcome the high costs of treatment implementation.

INTRODUCTION

Artificial regeneration technology strives to minimize regeneration costs and maximize seedling performance—regeneration efficiency. The dilemma of unsatisfactory oak regeneration is a result of the failure to balance the competing objectives of cost and performance. The challenge for today's forester is to improve the one without compromising the other.

Commercial oak species of the Southern United States are typically regenerated naturally with shelterwood systems (Loftis 1990). However, artificial regeneration (i.e., hand-planting) of oak is seldom considered because adequate seedling performance in the field is difficult to obtain (Boyette 1980). Oak nursery culture today places much emphasis on a seedling's ability to survive and grow after planting. Since stem caliper is indicative of root mass (Coutts 1987), a stem diameter of 12 millimeters has been recommended to maximize field performance of oak (Johnson 1988).

Nursery technology of oak has yet to produce affordable stock that is easily planted and demonstrates strong seedling performance. If regeneration costs were not a significant component of a silvicultural system, it would be justifiable to plant large saplings or small trees instead of seedlings. However, contemporary nursery cultural practices seem to produce seedlings at their plantable limits, such as with oaks. Moreover, planting small oak seedlings should be less expensive and less exhausting, although they will not have the stem caliper and root bulk likely to promote high survival and growth (Johnson 1988).

Bulky oak root systems are encouraged within current nursery practices. In this scenario, there are two approaches that can be utilized in order to properly plant the seedling. Either some sort of corrective strategy (i.e., field pruning) must be performed or the planting hole must be opened to a sufficient size. If neither of these is performed, root deformation (i.e., root balling or j-rooting) will occur. Some have suggested that root deformation may not be deleterious to a seedling's short- or long-term performance (Haase and others 1993). Root deformation is not condoned, although it is obviously more acceptable than to plant seedlings at a shallow depth. Perhaps some sort of root restriction strategy, such as variation in seedbed density, may be practically applied within future nursery cultural practices.

This study's objectives were to: (1) observe the effects of seedbed density on root morphology and subsequent root-handling treatments, (2) analyze costs and benefits, and (3) determine treatment(s) of maximum regeneration efficiency.

METHODS

Seeds of cherrybark oak (*Quercus falcata* var. *pagodifolia* Ell.) and northern red oak *(Quercus rubra* L.) were purchased in November 1992, stored at 5 ^{o}C until sowing, and sown at Whitehall Forest, Athens, GA, in December 1992. In November 1993, the seedlings were lifted and placed in cold storage. In December 1993, the northern red oak seedlings were planted on a sloping, shelterwood site having a basal area of 22 square meters per hectare located at Bent Creek Experimental Forest, Asheville, NC. The cherrybark oak seedlings were planted on a level shelterwood site having a basal area of 9 square meters per hectare managed by T&S Hardwoods, Inc., Milledgeville, GA.

A randomized, complete block design was employed, where seedlings from each of the five seedbed densities were subjected to three root-handling treatments with four replications of four seedlings per treatment (240 seedlings per species). The five nursery densities were 100, 169, 256, 400, and 529 seedlings per square meter. The three root-handling treatments were root balling (j-rooting), heavy root pruning (9 centimeters from the root collar), and dug-hole planting (no root pruning or balling).

Measurements

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The main establishment cost variables were seedling price (dollars), seedling weight (grams), planting rate (seconds per seedling). Another variable, considered only in total cost estimation, was site preparation cost. Stem heights (centimeters) and ground-line diameters (millimeters) were taken at planting, and in October 1994 and 1995.

Analyses

Data were analyzed using analysis of variance (ANOVA, SAS Institute, Inc. 1988) and Tukey's test for means comparisons of main effects. All analyses were conducted with a 95 percent significance level. If the interaction between main effects was significant, the data were reanalyzed via one-way ANOVA. Initial size was used as a covariate.

The conservative land value ($827 per hectare for the cherrybark oak site; $1,217 per hectare for the northern red oak site) provided an assessed cost for bare forest land, designated to continue as such (Georgia Department of Revenue 1996). Site preparation was not required at the Indian River site; however, a herbicide application was needed for understory control at Bent Creek at an estimated cost of $69 per hectare.

The estimated purchase price for bare-root oak seedlings (about $100 per 1,000 seedlings) was obtained for oak stock grown at a density of 256 seedlings per square meter. Based on their density in proportion to the 256-per-square-meter density, seedlings from 100, 169, 400, and 529-per-square-meter densities were priced at $256, $151, $64, and $48 per 1,000, respectively. At an assumed hourly rate of $15 per hour, planting 240 seedlings took 2.2 hours for cherrybark oak, and 2.0 hours for northern red oak, at a spacing of 1.8 meters by 1.8 meters (2,989 stems per hectare), for a total planting cost of $415 per hectare ($139 per 1,000 seedlings) and $380 per hectare ($127 per 1,000 seedlings) for cherrybark oak and northern red oak, respectively. Half of the total planting cost was equally assigned to each of seedling weight and planting rate, because weight and rate both affect planting time.

The following equations were used to calculate adjusted cost, benefit, and cost-over-benefit for each measurement year, respectively:

$$C=Cb*(1+i)**t$$

$$B=TPH*S*\Sigma((3.14159*(r**2)*h)/2)$$

$$COB=C/B$$

where

C is compounded total cost (dollars per hectare),
Cb is total cost (dollars per hectare),
i is an assumed interest rate (i=8 percent),
t is the time period of cost compounding (t=2 years),
B is stand volume (cubic decimeters per hectare),
TPH is trees per hectare,
S is proportion of surviving stems,
r is individual-tree stem radius (decimeters),
h is individual-tree height (decimeters), and
COB is cost-over-benefit (dollars per cubic decimeter).

The COB ratio is similar to the inverse of the benefit-cost ratio (Clutter and others 1983). The COB index, however, retains the units to provide a basis for meaningful comparisons among other regeneration treatments not considered in this study. The treatment with the lowest COB value, if significantly different from the other treatments, was considered optimum.

RESULTS

Seedlings from the two highest seedbed densities were lightest in weight for both species (table 1). The dug-hole method of planting was significantly slower ($p \leq 0.05$) than the other planting methods for both species. Second-year survival and diameter of cherrybark oak seedlings from 100-per-square-meter density were significantly greater than those of the highest density. Northern red oak survival results indicated that trimmed seedlings from the 529-per-square-meter density and dug-hole seedlings from the 256-per-square-meter density were significantly greater than dug-hole seedlings from the 400-per-square-meter density. Second-year diameters and heights did not differ significantly among treatments.

Total cost differed significantly among density and root-handling treatments for both species (table 2). The lowest density and dug-hole planting had the largest significant values for total cost at year 2 for both species. Second-year benefit (stand volume) for the lowest seedbed density was significantly greater than those of the other seedbed densities for cherrybark oak, while year-2 benefits did not differ significantly among treatments for northern red oak.

Second-year COB values for seedling cost (table 3) were significantly greater for the density of 100 per square meter versus other densities for both species. The highest density had a significantly lower second-year, seedling transport COB value than the other densities for northern red oak. Second-year COB values for planting rate indicated that the dug-hole method was significantly greater than those of the other root-handling treatments for both species. Second-year total cost COB values did not differ significantly among treatments.

DISCUSSION

Seedlings from low seedbed densities in our study were smaller than was expected, since fertilization was not included in the nursery culture. Smaller, lighter-weight seedlings, grown in high density seedbeds, allowed the planter to carry more seedlings to the planting location, reducing planting costs. Moreover, hoedad planting required the least amount of time for hole preparation, lowering planting costs. Therefore, while a treatment's benefit may not be greatly increased with time, lowering costs can serve to improve a treatment's chances of being selected as optimum.

Since weight tends to be positively correlated with volume, seedling transport COB values should be expected to increase with decreasing density. In fact, costs (determined by weight) divided by yield (determined by the parabaloid

Table 1—Second-year costs and benefits for cherrybark and northern red oaks

		Cherrybark oak						Northern red oak					
		Costs			Benefits			Costs			Benefits		
Density	Treat-ment	SC[a]	ST[a]	P[b]	S[a]	D[a]	H[ns]	SC[a]	ST[a]	P[b]	S[a*b]	D[ns]	H[ns]
529	Balled	48	7	18	33	5	33	48	9	17	56	4	19
	Trimmed			8	31	5	41			16	100	4	21
	Dug-hole			65	56	4	28			55	88	5	21
400	Balled	64	8	17	56	4	31	64	10	17	81	4	20
	Trimmed			18	50	4	36			16	75	4	21
	Dug-hole			63	69	4	25			54	44	5	19
256	Balled	100	14	20	56	4	31	100	11	15	67	4	18
	Trimmed			21	39	4	35			13	63	5	23
	Dug-hole			62	75	5	34			54	100	5	24
169	Balled	151	19	17	42	6	42	151	14	17	81	5	18
	Trimmed			16	63	5	34			14	81	5	22
	Dug-hole			58	46	5	39			57	83	5	18
100	Balled	256	14	17	58	5	39	256	21	16	69	6	22
	Trimmed			18	67	5	41			15	75	4	16
	Dug-hole			63	58	6	40			64	50	5	19

SC=seedling cost (dollars per 1000 seedlings); ST=seedling transport (grams per seedling); P=planting rate (seconds per seedling); D=diameter (millimeters); H=height (centimeters); S=survival (percent); a=density treatments differed ($p<0.05$); b=root-handling methods differed ($p<0.05$); ns=insignificant.

Table 2—Second-year costs (costs in dollars/hectare) and benefits for cherrybark and northern red oaks

		Cherrybark oak					Northern red oak				
		Costs			Benefits		Costs			Benefits	
Density	Treat-ment	SC[a]	ST[a]	P[b]	Tc[a,b]	dm^3/ha	SC[a]	ST[a]	P[b]	Tc[a,b]	dm^3/ha
529	Balled	165	150	120	1410	5.3	165	165	135	1995	2.4
	Trimmed			150	1410	4.2			120	1980	5.1
	Dug-hole			480	1770	3.8			450	2370	6.5
400	Balled	225	165	135	1485	3.6	225	165	150	2070	3.8
	Trimmed			135	1485	4.2			135	2055	3.9
	Dug-hole			480	1830	4.2			450	2430	2.9
256	Balled	345	270	150	1740	3.3	345	195	120	2205	3.0
	Trimmed			165	1740	3.8			105	2160	5.0
	Dug-hole			450	2025	7.1			465	2340	12.6
169	Balled	525	360	135	1980	7.1	525	255	135	2445	4.1
	Trimmed			120	1965	6.6			120	2415	4.8
	Dug-hole			435	2280	6.5			420	2550	4.4
100	Balled	900	270	135	2265	7.2	900	345	135	2895	5.0
	Trimmed			135	2295	8.1			120	2880	2.1
	Dug-hole			465	2580	13.7			525	3060	3.8

TC=total costs; a=density treatments differed ($p<0.05$); b=root-handling methods differed ($p<0.05$); ns=insignificant.

Table 3—Second-year cost-over-benefit means for cherrybark and northern red oaks

		Cherrybark oak				Northern red oak			
		COB				COB			
Density	Treatment	SC[a]	ST[ns]	P[b]	TC[ns]	SC[a]	ST[a]	P[b]	TC[ns]
		—Dollars per cubic centimeter—				*—Dollars per cubic centimeter—*			
529	Balled	94	88	74	794	99	100	83	1171
	Trimmed	67	54	52	560	38	39	25	438
	Dug-hole	50	50	151	544	35	36	95	482
400	Balled	65	47	37	430	63	50	39	573
	Trimmed	89	76	50	600	82	59	54	748
	Dug-hole	176	166	353	1455	150	120	297	1571
256	Balled	127	110	54	140	190	116	64	1185
	Trimmed	191	177	77	975	142	60	52	866
	Dug-hole	49	37	65	289	44	25	54	312
169	Balled	109	76	27	412	143	67	37	655
	Trimmed	96	65	22	359	126	57	28	571
	Dug-hole	120	84	100	526	187	97	162	978
100	Balled	168	58	25	434	255	114	43	839
	Trimmed	119	39	17	305	472	186	65	1515
	Dug-hole	284	72	152	816	406	163	231	1480

a=density treatments differed ($p<0.05$); b=root-handling methods differed ($p<0.05$); ns=insignificant.

volume yield equation) should be linearly related. In our study, cherrybark oak followed this linear trend, but northern red oak gave spurious results.

Benefits, unlike costs, have potential to increase linearly, exponentially, or remain constant. In our study, benefit was expressed in terms of total stem volume, but it also may be expressed on an individual-seedling basis. Thus, the importance of the yield equation is evident: it combines the variables and ranks them according to their relative effect on merchantable production (survival >> diameter > height).

To be considered profitable, growth in benefit for a given treatment should exceed the growth in cost, which is fixed by the given interest rate (8 percent in our study). Cherrybark oak was more profitable in time than was northern red oak, due to an average 36 percent increase in yield over 2 years, compared to an average 10 percent increase for northern red oak. Moreover, additions of extraneous costs (i.e., land costs) to total costs seem to distort the cost influence within COB analysis, and to diminish the cost influence from the variables of interest within COB analysis.

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PHOTOSYNTHESIS AND BIOMASS ALLOCATION IN OAK SEEDLINGS GROWN UNDER SHADE

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Abstract—Northern red oak (*Quercus rubra* L.) (NRO) and white oak (*Q. alba* L.) (WO) acorns were sown into wooden plots and grown under 30 percent shade screen (30 percent S) or 70 percent shade screen (70 percent S). Seedlings grown under full sun were the controls (C). At the end of the first year, the 30 percent S NRO had 30 percent greater seedling dry weight (DW) than C seedlings. No growth differences existed between these two treatments after 2 years. Compared to C, 70 percent S NRO had a 40 percent lower net photosynthetic rate (A), twofold less seedling DW and leaf number, and fourfold less lateral root DW after 2 years. Dry weight biomass allocation to lateral roots increased from 17 percent at the end of the first growing season to 22 percent after 2 years for both the C and 30 percent S NRO. The 70 percent S seedlings, however, allocated only 8 percent DW to lateral roots for both years. White oak seedlings responded similarly to shade as NRO seedlings. The 70 percent S WO had 30 percent lower A and fourfold less lateral root DW than the controls after 2 years. At the end of the second year, DW biomass allocation to lateral roots was 12, 7, and 5 percent, respectively, for C, 30 percent S, and 70 percent S WO seedlings. The impact of shade (reduced light intensity) on seedling growth of both oak species was discussed in terms of A, photoprotection, and DW biomass allocation.

INTRODUCTION

For the last three decades various silvicultural practices have been suggested to improve the success of natural and artificial regeneration of northern red oak (*Quercus rubra* L.) (NRO) on high-quality mesic sites. Several factors have been implicated in the less-than-satisfactory results of NRO regeneration. Competition for light between NRO seedlings and other hardwood species (such as *Acer saccharum* Marsh., *A. rubrum* L., and *Liriodendron tulipifera* L.) is the one most commonly mentioned in the literature (Barton and Gleeson 1996, Loftis and McGee 1993). Indeed, full-sun-grown NRO seedlings have higher net photosynthetic rates (A) than shaded seedlings (Crunkilton and others 1992, Kubiske and Pregitzer 1996, McGraw and others 1990). Yet, there still exist controversial results on the effects of shade on NRO growth. For example, Gottschalk (1985, 1987) reported that NRO seedlings receiving 70 percent of full sunlight grew better than seedlings receiving 8 to 57 percent or 94 percent of light. Similar contradictions exist for other *Quercus* species. Jarvis (1964) concluded that sessile oak [*Q. petraea* (Matt.) Liebl.] is intolerant to light intensity greater than 56 percent, whereas Gross and others (1996) reported that root collar diameters were smaller in sessile and pedunculate oak (*Q. robur* L.) seedlings grown under 50 percent shade for 3 years.

Even when oak seedlings are outplanted on clearcut sites, their poor initial growth results in their becoming overtopped by herbaceous vegetation and other faster growing hardwood species. Use of large size nursery stocks in the artificial regeneration practice has been suggested as a method of improving slow initial growth (Farmer 1975, Foster and Farmer 1970). Kormanik and others (1994) reported a nursery protocol that produced large-size oak seedlings as compared to seedlings used in various studies (Farmer 1979, Gottschalk 1985, Teclaw and Isebrands 1993). Nevertheless, shelterwood planting has been recommended as an alternative to outplanting oak seedlings on clearcut sites for various reasons (Loftis and McGee 1993, Teclaw and Isebrands 1993). However, these shaded oaks did not have fast growth even several years after release (Loftis and McGee 1993).

Chlorophyll bleaching has been reported to occur in shade leaves as well as in sun leaves formed from shade buds in the released understory plants. In other words, the sudden improvement of light intensity and quality resulting from overstory canopy removal actually imposes damage to the released plants. During the last decade, it has been well documented that under conditions when absorbed light energy cannot be fully utilized for photochemical reactions in photosynthesis, the xanthophyll cycle-dependent and pH-dependent dissipation of excessive energy prevents photo-oxidative damage to chlorophyll, chloroplasts, and cells. Of the three carotenoid pigments in the xanthophyll cycle, zeaxanthin (Z) and antheraxanthin (An) can dissipate excess energy but violaxanthin (V) cannot. Under light conditions, the de-epoxidation of V to Z via the intermediate An is catalyzed by de-epoxidase in the presence of ascorbate and low thylakoid lumen pH. Thus, the xanthophyll pool size and the ratio between Z+An and Z+An+V have been used to describe a leaf's photoprotection capacity (Demig-Adams and Adams 1996). Indeed, several reports showed that shaded leaves have lower levels of xanthophyll cycle pigments and smaller ratio of Z+An to Z+An+V as compared to sun leaves (Demig-Adams and Adams 1996, Faria and others 1996). The objectives of this study are to use the protocol of Kormanik and others (1994) to grow NRO and white oak (*Q. alba* L.) (WO) seedlings under different shade conditions and to evaluate the effects of shade on photosynthesis and biomass allocation.

MATERIALS AND METHODS

Seedling Growth and Harvest

In January 1993, 16 acorns of NRO or WO were sown into 1 meter by 1 meter by 0.6 meter wooden plots at a depth of

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1 centimeter below soil surface. Seedlings began to emerge by mid-March. The study was a complete random design with three treatments and two replications. A total of 12 plots were used for each species. In early April, a layer of neutral density screen was draped over a wooden frame 3.3 meters in height. Four plots were enclosed in each frame with a 0.6-meter distance between plots and a 0.8-meter distance between plots and the screen. The extent of shade was created by screens of different densities. Maximal photosynthetic active radiation, measured by a LiCor quantum sensor, for 30 percent shade (30 percent S) and 70 percent shade (70 percent S) treatments was 1100 $\mu E/m^2.s$ and 550 $\mu E/m^2.s$, respectively. The full sun control (C) had greater than 1800 $\mu E/m^2.s$. A gap of 0.3 meters was left between the ground and the lower edge of the screen to help air circulation. Seedlings were watered and fertilized according to the protocol of Kormanik and others (1994). The screen was lifted after leaf abscission in December 1993 and placed back in early April 1994.

In early December of 1993, seedlings were harvested from two of four plots for each species in each treatment. Care was taken to minimize root loss during harvest. Seedlings were separated into stems (with branches), leaves, taproots, and lateral roots. Each seedling component was oven dried at 95 °C until constant weight was obtained. Leaf area was measured with a portable CID Leaf Area Meter. The rest of the seedlings were grown for another year and harvested in December 1994. Dry weight for each seedling component was obtained.

Photosynthesis and Leaf Pigments

A portable LiCor 6200 Infrared gas analyzer was used to measure net photosynthetic rate (A) from recently mature leaves still attached to seedlings. In early September 1994, developing leaves of elongating flushes and mature leaves of the latest mature flushes from NRO seedlings grown under full sun were harvested throughout a day and immediately frozen in liquid N_2. Procedures for leaf pigment extraction and analysis were modified from the method by Gilmore and Yamamoto (1991). Ethanol (95 percent) and $CaHCO_3$ were used to extract pigments. A Dionex AI- 450 High Performance Liquid Chromatograph with a 4.5 millimeter by 25 centimeter Zorbax non-endcapped C18 column was used. The gradient system used was as followed: 0 to 6 minutes, eluent A (acetonitrile : methanol, 80 percent : 20 percent); 6 to 9 minutes, eluent A to eluent B (methanol : ethyl acetate, 68 percent : 32 percent); 9 to 15 minutes, eluent B. Flow rate was 2 milliliters per minute for both eluents. Pigments were detected at 445 nanometers. Retention times (in minutes) are: neoxanthin 2.4, violaxanthin 2.8, antheraxanthin 3.7, lutein 4.7, zeaxanthin 5.0, chlorophyll b 9.4, chlorophyll a 11.0, α-carotene 13.9, and β-carotene 14.1.

RESULTS AND DISCUSSION

Seedling Growth

Growth parameters of NRO and WO seedlings grown under different shades were presented in tables 1 to 4. Regardless of treatments, mean seedling size and weight for both species in this study are much greater than those reported in the literature (Farmer 1975, 1979; Gottschalk 1985, 1987; Teclaw and Isebrands 1993). The NRO seedlings were similar in size to the “1-0 large” seedlings classified by Johnson and others (1984). Because this study was designed for 2 years, the planting density used was about one-fourth of the prescribed density by Kormanik and others (1994).

The screen used in this study only decreased light intensity but did not change light quality. The 30 percent S grown NRO were significantly greater in total leaf area per seedling, total seedling dry weight (DW), and stem plus branch DW than the controls in 1993 (table 1). Although not statistically

Table 1—Effects of shade on first-year growth of northern red oak seedlings

Variable measured	Full sun	30% shade	70% shade	p-Value
Height (cm)	100.7a[a]	139.5a	100.8a	.0513
Groundline diameter (mm)	14.5a	16.4a	11.7b	.0063
FOLR number[b]	16.4a	17.8a	13.8a	.4209
Taproot DW[c] (g)	62.6a	70.1a	38.9b	.0077
Lateral root DW (g)	28.5a	34.2a	9.4a	.0671
Leaf DW (g)	34.9a	38.5a	23.2a	.0403
Leaf number	53.2a	50.1a	34.5a	.1925
Leaf area (cm^2)	3237.0b	4590.0a	3381.0b	.0016
Average leaf area (cm^2)	66.3a	93.2a	98.8a	.0795
Stem and branch DW (g)	48.1b	85.2a	34.5b	.0009
Seedling DW (g)	174.1b	228.0a	105.9c	.0029

[a] Least-square means for a given variable are not significantly different at the 0.05 experimentwise level using the Bonferroni approach when each pairwise contrast is tested at the 0.05/3 = 0.0167 level.
[b] First-order lateral root.
[c] Dry weight.

significant, these 30 percent S seedlings were generally larger in each growth parameter than C except for leaf number. This trend was less obvious for the second year (table 2). The 30 percent shade screen probably provided a cooling effect on the oaks during hot weather of the 1993 summer, thus resulted in more growth than controls. Northern red oak grown at 23 °C/23 °C (day/night) for 4 months had 60 percent greater seedling DW than those grown at 29 °C/23 °C (Farmer 1975). Hodges and Gardiner (1993) also reported that full-sun-grown *Q. pagoda* Raf. seedlings were smaller than those under 53 percent sun, but larger than seedlings grown under 27 and 8 percent sun.

Northern red oak seedlings of 70 percent S were consistently smaller in taproot and total seedling DW than controls for both years. At the end of the second year, effects of 70 percent shade on decreasing DW growth were significant in all seedling components with the exception of average individual leaf DW (table 2). Fewer leaves and larger individual leaf were observed in 70 percent S seedlings as compared to C and 30 percent S seedlings. Similar effects of shade on leaf number and area were reported with pedunculate oak (Ziegenhagen and Kausch 1995). The specific leaf weight for C, 30 percent S, and 70 percent S seedlings were 10.8, 8.4, and 6.9 mg/cm^2, respectively. Greater average leaf area, smaller specific leaf weight, and thinner leaf have been observed in several oak species grown under shade (Ashton and Berlyn 1994, Carpenter and Smith 1981, Farmer 1975).

Unlike NRO seedlings, the 30 percent S treatment did not increase WO growth over that of C (tables 3, 4). Lateral

Table 2—Effects of shade on growth of northern red oak seedlings for 2 years

Variable measured	Full sun	30% shade	70% shade	p-Value
Height (cm)	142.7a[a]	171.5a	160.6a	.3566
Groundline diameter (mm)	23.1a	22.9a	17.8a	.0281
Taproot DW[b] (g)	195.2a	186.6a	92.6b	.0176
Lateral root DW (g)	120.6a	122.0a	23.8b	.0053
Leaf DW (g)	52.3a	56.9a	38.5b	.0145
Leaf number	157.3a	140.8a	74.3b	.0019
Average leaf DW (g)	0.34a	0.42a	0.53a	.0171
Stem and branch DW (g)	154.5ab	177.0a	114.2b	.0275
Seedling DW (g)	522.6a	542.5a	269.1b	.0063

[a] Least square means for a given variable are not significantly different at the 0.05 experimentwise level using the Bonferroni approach when each pairwise contrast is tested at the 0.05/3 = 0.0167 level.
[b] Dry weight.

Table 3—Effects of shade on first-year growth of white oak seedlings

Variable measured	Full sun	30% shade	70% shade	p-Value
Height (cm)	36.9a[a]	45.7a	37.5a	.2657
Groundline diameter (mm)	9.3a	9.9a	7.4b	.0133
FOLR number[b]	10.0a	9.4a	7.8a	.1649
Taproot DW[c] (g)	33.9a	37.1a	19.5a	.0619
Lateral root DW (g)	3.1a	2.7ab	1.5b	.0280
Leaf DW (g)	8.6ab	10.2a	6.4b	.0264
Leaf number	45.0a	53.8a	42.1a	.0811
Leaf area (cm^2)	965.0a	1309.0a	893.0a	.0573
Average leaf area (cm^2)	21.0a	24.9a	21.3a	.3242
Stem and branch DW (g)	11.3ab	14.9a	7.1b	.0278
Seedling DW (g)	56.9a	64.8a	34.4a	.0353

[a] Least-square means for a given variable are not significantly different at the 0.05 experimentwise level using the Bonferroni approach when each pairwise contrast is tested at the 0.05/3 = 0.0167 level.
[b] First-order lateral root.
[c] Dry weight.

Table 4—Effects of shade on growth of white oak seedlings for 2 years

Variable measured	Full sun	30% shade	70% shade	p-Value
Height (cm)	95.0a[a]	98.6a	101.0a	.9420
Groundline diameter (mm)	18.1a	17.3a	14.0a	.1235
Taproot DW[b] (g)	120.3a	108.6a	62.4a	.0734
Lateral root DW (g)	36.3a	30.2ab	7.6b	.0215
Total leaf DW (g)	25.2a	24.3a	13.3a	.1352
Regular leaf DW (g)	15.1a	19.4a	8.4a	.0567
Recurrent leaf DW (g)	10.1a	4.9a	4.9a	.3454
Total leaf number	149.8a	154.7a	72.4a	.1268
Regular leaf number	131.0a	144.0a	60.7a	.0964
Recurrent leaf number	18.8a	10.7a	11.7a	.9233
Avg regular leaf DW (g)	0.11a	0.14a	0.14a	.0513
Avg recurrent leaf DW (g)	0.54a	0.46a	0.42a	.2837
Stem and branch DW (g)	80.0a	90.7a	52.7a	.2701
Seedling DW (g)	261.8a	253.8a	136.0a	.1095

[a] Least square means for a given variable are not significantly different at the 0.05 experimentwise level using the Bonferroni approach when each pairwise contrast is tested at the 0.05/3 = 0.0167 level.
[b] Dry weight.

root DW growth was consistently less in 70 percent S seedlings than C for both years (tables 3, 4). In 1994, we noticed that some WO recurrent flushes had individual leaves with much greater area than most leaves. These extra large-area leaves (recurrent leaves) were threefold to fivefold greater in DW than the regular leaves (table 4). Control seedlings seemed to have more recurrent leaves than shaded seedlings. The specific leaf weights for C, 30 percent S, and 70 percent S seedlings in 1993 were 8.9, 7.8, and 7.2 mg/cm^2, respectively. Similar to NRO, WO seedlings grown under shade had fewer leaves, smaller individual leaf DW, and less total leaf area (tables 3, 4).

There were great variations in seedling size even within a wooden plot. The effects of shading on growth can be masked by these variations. When percents of DW allocated to each seedling component were examined, it was clear that DW allocation to lateral roots was affected the most by shading with both oak species in both years (table 5). It has been reported that shading decreased oak DW allocation to root system (Gottschalk 1987, Hodges and Gardiner 1993, Ziegenhagen and Kausch 1995). Our study probably is the first to show that shading decreased DW allocation to lateral roots but not taproots in oaks. Messier and Puttonen (1995) reported shading decreased DW allocation to fine-root biomass in *Betula pubescens* Ehrh. and *B. pendula* Roth

Table 5—Effects of shade on percent dry weight biomass allocation within oak seedlings

	Full sun		30% shade		70% shade	
Variable measured	1 year	2 year	1 year	2 year	1 year	2 year
Northern red oak						
Lateral root	16.9	22.0	14.9	20.5	8.3	8.3
Taproot	37.2	39.9	32.1	38.1	38.5	37.3
Stem and branch	27.0	27.9	36.2	30.5	31.0	39.8
Leaf	18.9	10.2	16.8	10.9	22.2	14.6
White oak						
Lateral root	5.2	11.7	4.3	10.7	4.5	4.9
Taproot	61.1	50.1	57.4	46.8	57.4	50.9
Stem and branch	19.2	28.3	22.0	32.5	19.5	35.3
Leaf	14.5	9.9	16.3	10.0	18.6	8.9

grown under pine stands of different light availability. Thus, the underplanted oak seedlings with decreased lateral root growth would probably become less and less competitive for water and nutrient with established trees in the stands. High mortality of outplanted oaks in mixed hardwood stands as compared to that of pine stands and clearcut site planting has been observed by Kormanik and others (in press).

Photosynthesis

In this study, NRO A was not affected by the 30 percent shade treatment in either year (table 6). However, there was at least 30 percent decrease in A in 70 percent S NRO seedlings as compared to the controls. Effect of shade on decreasing A was more obvious with WO seedlings. Decreased oak A by shading, with or without change in light quality, has been reported in many studies (Crunkilton and others 1992, Kormanik and others (in press), Kubiske and Pregitzer 1996, McGraw and others 1990).

If leaf number and area were taken into consideration, the estimated A for 70 percent S NRO and WO seedlings were about 70 and 30 percent, respectively, of the controls for 1994 (table 6). These estimated A values are close to the value of 50 percent less seedling DW for both species grown under 70 percent S (tables 2, 4). Although WO has similar A to that of NRO, the slower growth by WO seedlings can be explained by the fact that WO seedlings have fewer leaves and smaller individual leaf area than NRO (table 6). Similar A's for WO and NRO were reported by Barton and Gleeson (1996) and Sung and others (1995).

Photoprotection

Levels of pigments in developing and mature leaves from full sun-grown NRO seedlings are presented in table 7. Mature leaves had twice as much chlorophyll a plus chlorophyll b (Chl a+b) as developing leaves. No significant differences in the levels in all the carotenoid pigments, expressed on the mol Chl a+b basis, were observed between developing and mature leaves (table 7). Only the xanthophyll cycle pigments exhibited diurnal patterns in both types of leaves. The Z+An to Z+An+V ratio was low in the dark and very high around noon. Values presented in table 7 were comparable to those found with cork oak leaves (Faria and others 1996). Judged from the xanthophyll pool size (Z+An+V) and the ratio between Z+An and Z+An+V, it is obvious that the photoprotection mechanism is more active in developing leaves than in mature leaves. Similarly, sun cork oak leaves are more photoprotective than shade leaves (Faria and others 1996). The effects of shading on the xanthophyll pool sizes and the diurnal patterns of Z+An to Z+An+V ratio will be examined for NRO and WO seedlings grown under different types of stands in the future.

CONCLUSIONS

Northern red oak and white oak seedlings grown under 70 percent shade had lower net photosynthetic rate, fewer leaves, and less specific leaf weight, seedling dry weight, and dry weight allocation to lateral roots as compared to those grown with full sun. Like most plants, developing and mature northern red oak leaves exhibit diurnal xanthophyll cycle for photoprotection. Greater dry weight growth with northern red oak seedlings than white oak is associated with the former having more and larger leaves. With the presence of large leaves on some of the recurrent flushes in white oak seedlings, dry weight growth can be increased because recurrent leaves have a higher net

Table 6—Effects of shade on oak net photosynthetic rate (A)

Light level	1993 Average A[a] µmol/m^2.s	1993 Estimated A[b] µmmol/seedling.h	1994 Average A µmol/m^2.s		1994 Estimated A µmmol/seedling.h
Northern red oak					
Full sun	10.1	11.76	10.5		18.34[c]
30% shade	10.3	17.02	10.4		25.40
70% shade	6.6	8.03	6.3		12.72
White oak:			(Regular)	(Recurrent)	
Full sun	10.2	11.89	11.5	15.1	13.40[d]
30% shade	8.9	14.71	9.7	10.7	11.11
70% shade	6.5	7.91	5.7	6.8	4.16

[a] Average of photosynthetic rates measured between June and October.
[b] Derived from average A x leaf area per seedling.
[c] Leaf area per seedling was calculated using the same specific leaf weight (g/cm^2) obtained from seedlings harvested in 1993.
[d] Derived from sum of estimated A for regular leaf and for recurrent leaf.

Table 7—Levels of chlorophyll and carotenoids in developing and mature leaves from northern red oak seedlings grown under full sun

	Time of day					
Pigment	5 am	9 am	11 am	2 pm	5 pm	9 pm
Developing leaf[a]						
Chl a+b, mol/m^2	174.3	143.4	168.1	163.1	147.2	165.1
Zeaxanthin (Z)[b]	5.1	21.8	33.8	33.8	41.7	8.5
Antheraxanthin (An)	4.8	17.0	17.8	22.8	26.8	8.4
Violaxanthin (V)	78.1	35.6	14.3	27.1	21.3	82.3
Z+An+V	88.0	74.4	65.9	83.7	89.8	99.2
Lutein	122.9	116.0	115.0	130.3	122.2	124.6
Neoxanthin	58.5	60.5	57.8	56.0	57.9	54.4
α-Carotene	1.8	2.4	2.3	2.6	2.2	1.6
β-Carotene	50.8	49.6	47.7	48.7	49.2	47.8
Total Carotenoid	322.1	302.9	288.7	321.3	321.3	327.6
Z+An/Z+An+V ratio	0.11	0.52	0.78	0.68	0.76	0.17
Mature leaf[c]:						
Chl a+b, mol/m^2	394.3	336.4	363.7	354.8	363.4	360.2
Zeaxanthin (Z)	4.6	8.3	12.5	29.1	16.8	6.7
Antheraxanthin (An)	4.8	8.8	8.2	11.4	9.3	5.9
Violaxanthin (V)	52.7	50.7	25.2	19.4	14.9	50.7
Z+An+V	62.1	67.8	65.9	59.9	51.0	63.3
Lutein	92.7	94.7	84.4	99.4	84.3	94.4
Neoxanthin	57.0	56.1	53.1	60.7	50.1	57.8
α-Carotene	1.1	1.1	1.4	1.4	1.1	1.1
β-Carotene	56.5	56.7	53.1	61.5	50.9	57.4
Total Carotenoid	269.4	276.3	258.0	282.8	237.5	273.9
Z+An/Z+An+V ratio	0.15	0.25	0.62	0.68	0.71	0.20

[a] Average of four developing leaves from an elongating flush. Flushes of similar developmental stages were used for analysis throughout the day. All leaves were between 5 and 20 percent of average mature leaf size.
[b] All carotenoid pigments are in mmol/mol Chl a+b.
[c] Average of three mature leaves from the latest mature flush; different sets of leaves were used throughout the day.

photosynthetic rate than regular leaves. Use of large-size planting stock and outplanting these seedlings on clearcut sites should improve success of artificial regeneration of oak species.

ACKNOWLEDGMENT

This research was funded partially by Department of Energy Grant DE-AI09-76SR00870 to Paul P. Kormanik and Shi-Jean S. Sung.

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EARLY GROWTH OF SHELTERED AND UNSHELTERED CHERRYBARK OAK ESTABLISHED BY PLANTING 1-0 BAREROOT AND 1-0 CONTAINERIZED SEEDLINGS, AND BY DIRECT-SEEDING

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Abstract—Early growth of sheltered (TUBEX® tree shelters) and unsheltered cherrybark oak (*Quercus falcata* var. *pagodaefolia* Ell.) seedlings was compared in this study. Seedlings were established by: (1) direct seeding, (2) hand planting two types of containerized seedlings—those grown in (a) Rootrainer® books (20 cubic inch volume) and (b) greenhouse-forced seedlings grown in large tree-pots (150 cubic inch volume)—and (3) conventional hand planting of bareroot seedlings. With the exception of the greenhouse-forced seedlings that were not sheltered, tree shelters were applied to each seedling type. After five growing seasons, mean height and diameter at breast height (d.b.h.) of all trees was 8.8 feet and 2.2 inches, respectively. There were no significant differences in 5-year heights or diameters between sheltered and unsheltered seedlings. However, the comparative rates of growth of sheltered and unsheltered seedlings reversed after the sheltered seedlings emerged from the shelter tops. During 1993, height growth of the sheltered seedlings, before they emerged from the shelters, was significantly greater than that of unsheltered seedlings for all establishment methods. Except for direct-seeded seedlings, height growth during 1995 and 1996 was significantly greater for previously unsheltered seedlings. Deer-browse was not a factor in this study. After five growing seasons, minimal differences in height and d.b.h. resulted from very different patterns of growth for sheltered and unsheltered cherrybark oak seedlings. Establishment by conventional bareroot seedlings and/or by direct seeding was not improved by the use of shelters or enhanced seedling types.

INTRODUCTION

Cherrybark oak is the most valuable bottomland oak native to Tennessee. It produces a higher percentage of high grade lumber than other species of bottomland red oaks. Attempts to use cherrybark oak in plantation culture have been disappointing. While survival has been satisfactory, early growth of transplanted seedlings is generally slow.

Tree shelters have been utilized by the British Forestry Commission since 1979 to improve survival and growth of planted oak trees (Tuley 1985). The initial cost of installing shelters—$4 to $6 each—(Smith 1993, Kays 1995) has limited their application to high-value species.

Lantagne (1991) found that rapid early height growth of sheltered northern red oak (*Q. rubra* L.) enabled seedlings to grow more quickly into dominant and codominant crown positions in a regenerating clearcut. Similar early height growth would allow planted cherrybark seedlings to overtop and suppress competing vegetation, a primary cause of slow growth. This study evaluates using tree shelters to stimulate early growth of cherrybark oak. Shelters were tested on seedlings established (1) as bareroot planting stock, (2) in containerized seedlings, and (3) by direct seeding. As a comparison, very large, greenhouse-produced, containerized seedlings were also planted.

METHODS

The study was established on The University of Tennessee Agricultural Experiment Station at Jackson, TN, on a previously cropped agricultural field, which was seeded to wheat as an interim cover crop. Soils in the study area are Grenada silt loam, eroded, gently sloping terrace phase (Tglossic Fragiudalf, fine-silty mixed thermic). The study design was an incomplete block with 10 replications of eight treatments. Each treatment plot consisted of six planting spots on an 8 foot by 8 foot spacing.

Cherrybark oak acorns were collected in Shelby County, TN, during the fall of 1990, by Tennessee Division of Forestry (TDF) personnel. The acorns were held in cold storage at the TDF nursery. In mid-January 1991, a sample from the bulk seedlot was separated by water flotation. Ten pounds of sound acorns were selected for this study. Five pounds of this sample were kept at the TDF nursery and used to produce the barerooted seedlings. Standard nursery practices were followed. The remaining acorns were maintained in cold storage until divided into thirds and utilized to produce seedlings under each of the following cultural systems:

Greenhouse-Forced Containerized Seedlings

Acorns were removed from cold storage on January 20, 1991, imbibed in water for 15 hours, and kept moist in a bucket until germination. Each day, all germinated acorns were transplanted into Zarn® tree containers (4 inches by 4 inches by 16 inches) filled with a pine bark growing media. Seedlings were grown under supplemental lighting (14-hour day length), watered as required, and fertilized weekly with a 200-parts-per-million solution of a 20-20-20 water soluble fertilizer. Temperatures suitable for growth were maintained using steam heat in winter and evaporative cooling during spring and summer.

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Containerized Seedlings

Containerized seedlings were produced using the same methods as the greenhouse-forced containerized seedlings with the following exceptions: acorns were removed from cold storage March 30, 1991, and, after germination, were seeded into Hillison® Rootrainer Books filled with a 1:1:1 ratio of peat moss, vermiculite, and perlite.

Direct-Seeding

On March 26, 1991, the remaining acorns were removed from cold storage and direct-seeded into their assigned field plots the following day. Two acorns were placed by hand in the bottom of a 1-inch-deep dibble bar slit at each planting spot and the slit was closed by foot pressure. The seeding dates for the containerized and direct-seeded seedlings were selected such that their emergence would coincide with that of the acorns sown in the nursery. In mid-June the less vigorous seedling was removed from each direct-seeded spot.

The containerized seedlings and the forced greenhouse seedlings were outplanted into assigned field plots in early October 1991. Barerooted seedlings were lifted on December 18, 1991, and stored until outplanted January 20, 1992.

Shelter Installation

Four-foot Tubex® tree shelters were installed during the spring of 1992 on assigned plots of bare-rooted, containerized and direct-seeded seedlings before they broke dormancy, with the following exceptions: (1) those direct-seeded seedlings designated for shelters at planting time (shelters were installed in early June 1991), and (2) the large greenhouse-forced seedlings were not sheltered. Eight treatments were evaluated:

(1) Bareroot seedlings with shelters and,
(2) without shelters.
(3) Containerized seedlings with shelters and,
(4) without shelters.
(5) Direct-seeded with shelters and,
(6) without shelters and also,
(7) with shelters installed at seeding.
(8) Greenhouse-forced seedling without shelters.

Control of competing vegetation was accomplished by mowing and directed spray applications of Roundup® herbicide around each seedling as required. Total height to the nearest 0.1 foot was measured after barerooted seedlings were planted, in 1991, and after their second, fourth, and fifth growing seasons. Diameter at breast height (d.b.h.) was measured after the fifth growing season. Data were analyzed with a randomized incomplete block model using Proc Mixed (SAS 1996). Least-square means were calculated and compared using pairwise t-tests ($P < 0.05$).

Age of the direct-seeded seedlings does not include their initial growing season in the field, so their "age" compares with the other seedling types that were produced in the nursery and/or greenhouse.

RESULTS

Initial Seedling Size

Seedling size after out-planting for seedlings grown under the various cultural systems is given in table 1. At the end of the initial growing season, height of direct-seeded seedlings that were sheltered (0.58 feet) was significantly ($P<0.05$) greater than that of unsheltered direct-seeded seedlings (0.44 feet).

Unsheltered Seedlings

Two years after outplanting, greenhouse-forced seedlings were the tallest of the seedling types at 4.1 feet, which was significantly taller than bareroot (2.3 feet), containerized (2.2 feet), and direct-seeded (1.9 feet) (table 2). By the fourth year these differences in total seedling height had disappeared. There were no significant differences among the d.b.h.'s of unsheltered seedlings.

Shelter Effects

After two growing seasons, both the sheltered bareroot and the containerized seedlings were significantly taller (5.0 feet, and 5.1 feet, respectively) than unsheltered seedlings (2.3 feet, and 2.2 feet, respectively) (table 2). However, the early height advantage of the sheltered seedlings, both bareroot and containerized, had disappeared after the fourth growing season. There were no significant differences in d.b.h. between sheltered and unsheltered seedlings (both bareroot and containerized) after five growing seasons.

Seedlings established by direct-seeding with shelters installed at planting, were significantly taller (3.6 feet) after two growing seasons than both the unsheltered seedlings (1.9 feet) and those having shelters installed after their initial growing season (2.5 feet). Similar to the sheltered

Table 1—Initial height and groundline diameter (after planting) of cherrybark oak seedlings produced by the indicated cultural systems (all seedlings 1-year-old)

Cultural system	Mean height	Mean groundline diameter
	Feet	*Inches*
Bareroot nursery	1.25	0.19[a]
Direct-seeded	0.44	0.12
Containerized	1.15	0.28
Greenhouse forced	3.50	0.39
Direct-seeded w/o shelter	0.44 a[b]	0.12
Direct-seeded w/shelter	0.58 b	0.11

[a] Measured after planting at ground-line (root collar measurement would have been larger).
[b] Mean heights of unsheltered direct-seeded seedlings and direct-seeded seedlings sheltered in the initial growing season differ significantly at P<.05.

Table 2—Height after 2, 4, and 5 years, and diameter at breast height (d.b.h.) at 5 years for sheltered and unsheltered cherrybark oak seedlings established by bare-root, direct-seeded, containerized, and greenhouse-forced stock

Seedling type	Shelter	Age 2 yrs	4 yrs	5 yrs	
		- - - Height (*ft*) - - -		- - - D.b.h. (*in*) - - -	
Bareroot	No	2.3 d[a]	6.7 a	8.7 a	0.9 a
Bareroot	Yes	5.0 a	6.9 a	8.6 a	1.0 a
Containerized	No	2.2 d	5.8 a	8.5 a	0.9 a
Containerized	Yes	5.1 a	6.5 a	8.6 a	1.0 a
Direct-seeded	No	1.9 d	6.7 a	8.5 a	0.9 a
Direct-seeded	Yes (1)[b]	3.6 c	6.1 a	8.3 a	0.9 a
Direct-seeded	Yes	2.5 d	7.3 a	9.5 a	1.1 a
Greenhouse-forced	No	4.1 b	7.0 a	9.7 a	1.1 a

[a] Means within columns not followed by the same letter differ significantly at P <0.05.
[b] Direct-seeded seedlings sheltered in the initial growing season.

and unsheltered treatments with both bareroot and containerized seedlings, total height differences had disappeared by the end of the fourth growing season.

Incremental Height Growth

Bareroot and container seedlings—Height growth of sheltered seedlings during the second growing season (while seedlings were still within the shelters) for both bareroot (2.1 feet) and containerized (1.8 feet) planting stock, was significantly greater than that of unsheltered seedlings (0.8 feet and 0.7 feet, respectively) (table 3). During the fourth growing season after all seedlings had emerged from the shelters, this pattern of growth had reversed, and unsheltered seedlings, from both bareroot (2.1 feet) and containerized (1.7 feet) stock had significantly greater height growth than did the sheltered seedlings (0.6 feet, and 0.4 feet, respectively) (table 3). After seedlings emerged from the shelters they developed crowns comparable to that of unsheltered seedlings during the first two growing seasons. While the sheltered

Table 3—Annual increment at indicated ages for sheltered and unsheltered cherrybark oak seedlings by establishment method

Seedling type	Shelter	Age 2 yrs	4 yrs	5 yrs
		- - - - - - - - Annual increment (*ft*) - - - - - - - -		
Bareroot	No	0.8 cd	2.1 a	1.9 bd
Bareroot	Yes	2.1 a	0.6 b	1.8 d
Containerized	No	0.7 d	1.7 a	2.5 ac
Containerized	Yes	1.8 b	0.4 b	1.9 bd
Direct-seeded	No	1.0 c	2.2 a	2.1 bcd
Direct-seeded	Yes	1.4 c[a]	2.2 a	2.5 ab
Direct-seeded	Yes(1)[b]	2.2 a	0.5 b	2.0 bd
Greenhouse-forced	No	0.3 d	1.9 a	2.8 a

[a] Means within columns not followed by the same letter differ significantly at P <0.05.
[b] Direct-seeded seedlings sheltered the first growing season.

seedlings were developing a crown above the shelter, there was a marked decrease in their height growth. During the fourth growing season the annual height growth of unsheltered seedlings (2.5 feet) was significantly greater than that of the sheltered seedlings, both for containerized (1.9 feet) and bareroot (1.8 feet).

Direct-seeded seedlings—Annual height growth in the second growing season, of direct-seeded seedlings which were sheltered when seeded (2.2 feet) was significantly greater than either seedlings that remained unsheltered (1.0 feet) or seedlings sheltered after their initial growing season (1.4 feet). As with the bareroot and container seedlings, this early pattern was reversed for the fourth growing season and disappeared in the fifth.

CONCLUSIONS

At the end of five growing seasons in the field, there were no significant differences in total height due to either shelters or seedling type. The early height growth advantage observed for sheltered seedlings was not evident at the end of this study. The development of a crown above the shelters took precedence over continued height growth, allowing the previously unsheltered seedlings to catch up. Establishment of cherrybark oak in west Tennessee by the conventional method, hand-planting bareroot seedlings, or by direct-seeding was not improved upon by either the use of shelters or by the use of containerized seedlings.

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ESTABLISHMENT OF PAULOWNIA PLANTATIONS USING FLOAT TRAY SEEDLINGS

Jeffrey W. Stringer[1]

Abstract—This study was designed to determine the effectiveness of using float tray seedlings, a relatively inexpensive type of containerized plug seedling, in establishing *Paulownia tomentosa* plantings. Cultural treatments including a control, hardwood bark mulch, a soil mixture, and a combination mulch/soil mixture were tested with and without 1-foot-tall tree shelters to determine their effects on growth and survival of *P. tomentosa* over a 3-year period. Tests were completed on four sites: three surface-mined sites and one alluvial bottom site in eastern Kentucky. Results showed an initial seedling survival rate of < 25 percent when seedlings were planted without a shelter and without a soil amendment. One-foot reusable tree shelters in combination with a soil amendment treatment produced significantly greater survival across all sites ($P<0.05$). After 3 years, survival was greater than 75 percent on a number of the sites tested. This study indicates that this type of planting stock can be considered as a viable option in the establishment of paulownia plantations.

INTRODUCTION

Since the mid-1970's, relatively high prices have been paid for *Paulownia tomentosa* trees and logs meeting export grade requirements (Stringer and Graves 1994). These prices spurred the development of both scientific and commercial projects involving the establishment and growth of paulownia plantations (ex. Beckjord 1984, Dong and van Buijtenen 1994, Stringer 1986). These projects have shown that *Paulownia* spp. can be used for a variety of different forestry applications and sites ranging from surface mine reclamation on relatively marginal sites to reforestation of highly productive alluvial bottomland sites.

Economic analysis of growing Paulownia for both domestic and export markets indicated that reasonable returns could be expected (Hardie and others 1989, Kays and others 1988, Johnson and others 1992). Rotation lengths were estimated to be between 10 and 20 years, and greater than 30 years for the production of logs meeting the requirements for domestic and export markets, respectively (Graves 1993). Rates of return, as is the case with all such analyses, are higher when initial establishment costs are kept to a minimum. However, initial efforts in plantation establishment of the genera used high-cost nondormant, containerized planting stock. The production, handling, planting, and initial care of this type of planting stock can be problematic, especially for large scale plantings. Low-cost alternatives, such as root cuttings (Stringer 1994a, b) and small plug-type planting stock, can be used to dramatically reduce establishment and maintenance costs. This study was designed to determine the effectiveness of using float tray seedlings, a relatively inexpensive type of containerized plug seedling, in establishing *Paulownia tomentosa* plantings on both marginal surface mine sites and an alluvial bottomland site.

METHODS

Tests were completed on four sites: three surface mined sites, and one alluvial bottom site in the Eastern Coalfield Region of Kentucky. All sites were dominated by Kentucky 31 tall fescue (*Festuca elatior* var. KY-31). The surface mined sites were generated through standard overburden handling procedures and grass and legume revegetation practices associated with contour mining for coal. Spoil material was composed of 3-year-old sandstone and shale overburden (pH > 5.8). The three sites included a north and south facing slope (slope percent 20 to 30) and a flat, highly compacted, contour bench. Soils on the alluvial bottomland site were mapped as a Grigsby series (coarse-loamy, mixed, mesic Dystric Fluventic Eutrochrept). These soils are typically loamy to fine-loamy, deep, and well-drained, formed from mixed alluvium from sandstone, siltstone, and shale.

Each site contained one replicate planting. A complete randomized block design (three blocks per site) was used to establish each replicate planting. Each block contained four main treatment plots consisting of eight trees. The plots had one of the following treatments: hardwood bark mulch, incorporated soil mix, combination of mulch and soil mix, and a control. The composted and ground hardwood bark mulch was applied 2.5 centimeter deep in a 1-meter square around each planting spot. The soil mix involved the mixing of potting soil in a 1:1 ratio with existing media in a hole 30-centimeters deep and 20 centimeters around each planting site. Each treatment plot was split into two subplots and the four trees in one of the randomly selected subplots received a 25-centimeter-tall Tubex$_{(TM)}$ tree shelter.

Float tray seedlings, a type of containerized plug seedling, were originated from a mixed collection of seed from nine local mother trees. Seeds were taken from cold storage and pretreated to initiate rapid germination, and sown onto standard potting mix in a seedling flat. The flat was covered with polyspun material to provide adequate moisture and light for germination (Stringer 1986). One-week-old seedlings were transplanted to 200-cell Styrofoam$_{(TM)}$ float trays and subjected to a 16-hour day length.

Previously existing vegetation on all planting sites was killed with glyphosate (Accord$_{(TM)}$) applied at the recommended rate. Five-week-old float tray seedlings were hand planted in early May and each of the treatments and shelters were applied at this time. No other cultural treatments were applied during the first growing season.

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Seedlings at all test sites were coppiced 2.5 centimeters above the groundline at the end of the 2nd growing season.

Survival and total height were measured 1 month after planting and at the end of the each growing season for 3 years. Standardized residual plots were used to determine variance homogeneity to locate potential outliers. Bonferroni's inequality was used to inflate "a priori" p-values for outliers and t-tests used to remove outliers. ANOVA (Type III SS) and LSD (t) and Wilcoxon 2-sample t-tests were employed to determine among treatment and among site differences ($P<0.05$). Survival percent was determined for each subplot and an arc sin transformation used for analysis (Steel and Torrie 1980). Comparisons among primary (soil amendments) and secondary (shelters) treatment effects were completed on data pooled over all planting sites as well as for within planting sites.

RESULTS AND DISCUSSION

Analysis of data pooled over all sites showed a significant difference ($P<0.01$) in survival between sheltered versus nonsheltered seedlings within all primary treatments except the control (fig. 1). This pattern was consistent throughout the experimental period and across all sites. Survival of nonsheltered seedlings among treatments was not significantly different, averaging approximately 25 percent after 2 years (fig 1c). This indicates a significant additive effect of the combination of tree shelters and a mulch and/or soil mix treatment. While mean survival for the soil mix treatment was less than that of the mulch or the combined treatment, no significant difference was found among them. Survival was not increased by using a combination of soil mix and mulch.

Data pooled over all sites showed first-year height growth averaged approximately 0.5 meter (fig 2a). A significant difference in seedling height after 1 year was found between sheltered versus nonsheltered seedlings across all treatments except for the soil mix treatment. However, the impact of the shelters on height growth was relatively short-lived. No significant differences in height, among treatments or between sheltered versus nonsheltered seedlings, were found after the first growing season (figs. 2b and 2c). After 2 years, total height averaged 1.71 meters over all treatments. Between the second and third growing season, trees were coppiced. The third-year data represent 1-year coppice growth averaging 2.81 meters for all trees. The second-year coppicing produced sprouth growth of a magnitude sufficient to establish a single main stem of the minimum length requirement of 2 meters for current export markets.

The short-lived effect of the shelters on height growth is probably a result of the fact that the trees emerged from the top of the 1-foot shelters during the first month after outplanting. While no significant difference in height between sheltered versus nonsheltered seedlings were found, there was a trend for the sheltered coppice sprouts to be taller than nonsheltered sprouts (fig. 2c). This may have been due to the extension in the length of the growing season provided to the coppiced trees by the shelters. Anecdotal observation found that sprouting initiated within the shelters approximately 1 to 2 weeks before sprouting of the nonsheltered trees. The difference in timing of coppice initiation may be have been responsible for the trend.

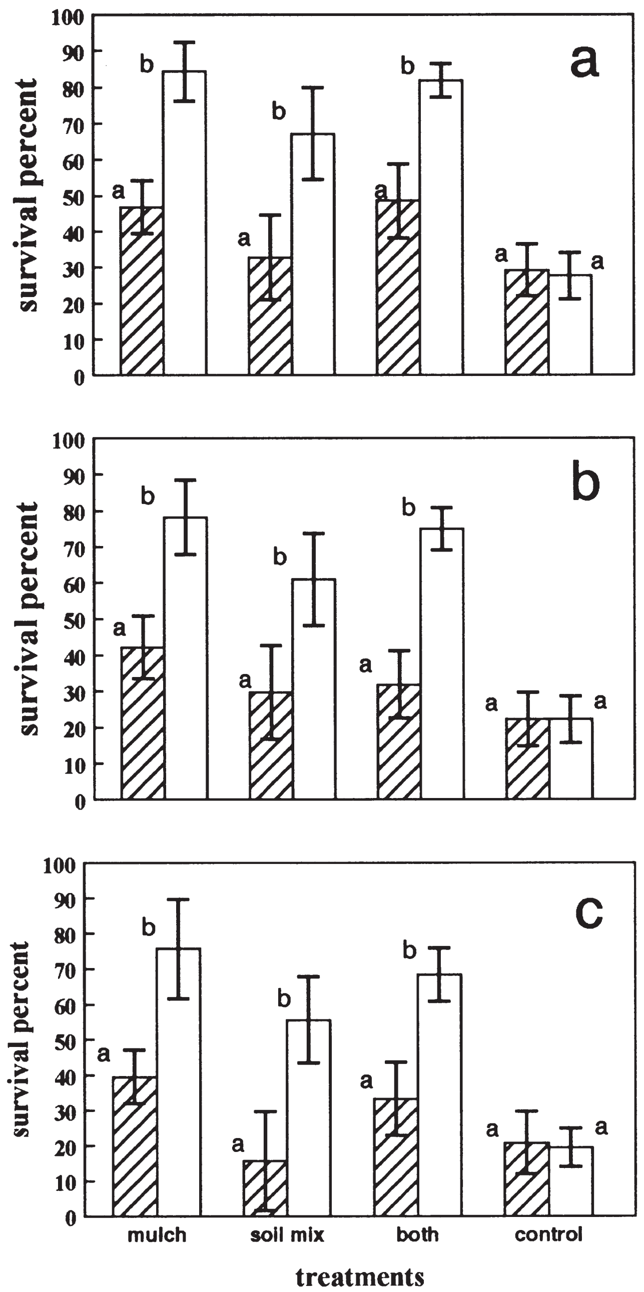

Figure 1—Survival percent of *Paulownia tomentosa* float tray seedlings. Bars (open=sheltered seedlings and lined=nonsheltered seedlings)and standard error bars represent data pooled over all sites for: (a) one month, (b) 1 year, and (c) 2 years. Bars with different letters represent significant differences ($P<0.05$) both within and among treatments.

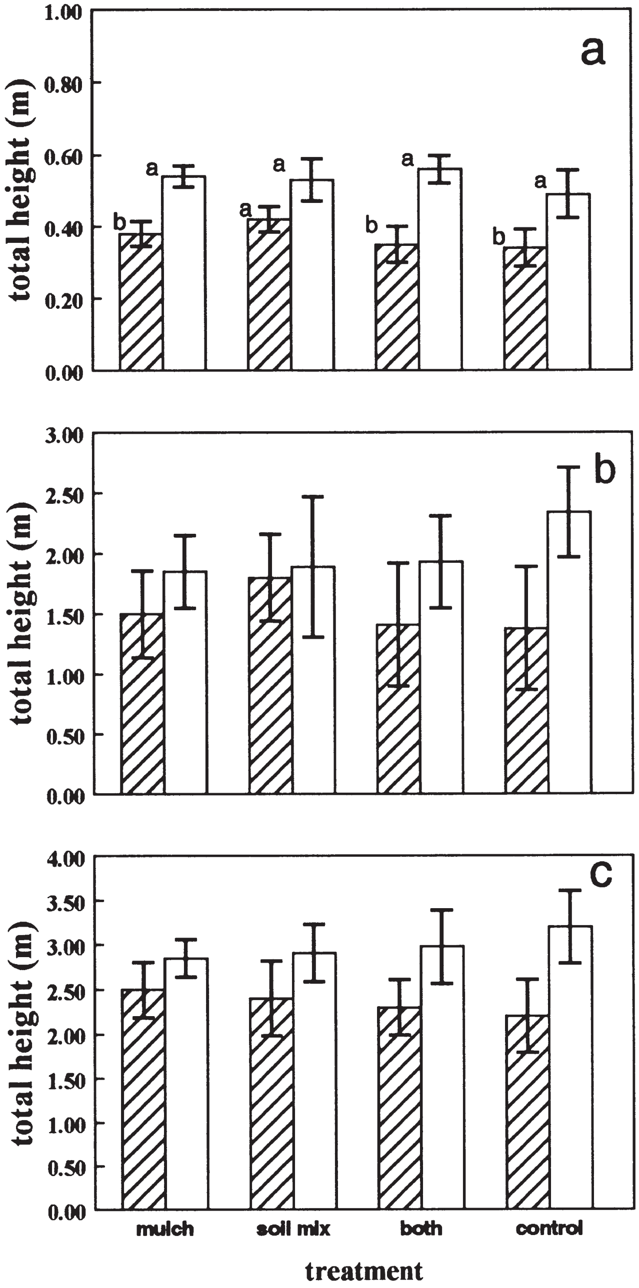

Figure 2—Total height of *Paulowina tomentosa* float tray seedlings. Bars (open=sheltered seedlings and lined=non-sheltered seedlings)and standard error bars represent data pooled over all sites for: (a) 1 year, (b) 2 years, and (c) 3 years. Bars with different letters represent significant differences (P<0.05) both within and among treatments.

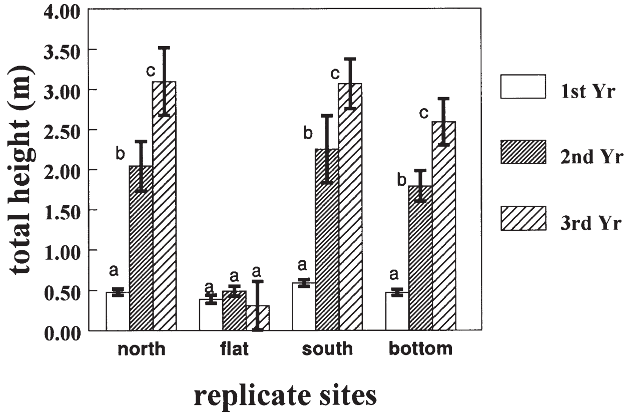

Figure 3—Differences in total height of *Paulowina tomentosa* float tray seedlings among test sites. Bars (open=sheltered seedlings and lined=nonsheltered seedlings) and standard error bars represent data pooled within sites. Bars with different letters represent significant differences (P<0.05) among years or sites.

After the first year there was a significant difference in height growth among sites (fig. 3). The seedlings on the flat surface-mined site, while exhibiting height growth equivalent to seedlings on the other sites during the first year, did not increase in height in subsequent years. This is consistent with other findings relating to tree growth on similar, highly compacted, surface-mined sites.

Results of analysis of the data within a replicate site showed similar results to those obtained from analyzing the data pooled over all sites. Figure 4 shows an example using 2-year height data from the south facing surface-mined site. No significant difference in total height between sheltered versus nonsheltered seedlings or among treatments was found.

CONCLUSIONS

Results of this experiment indicate that float tray seedlings can be used to establish *Paulownia tomentosa* on sloping surface-mined lands as well as alluvial bottoms in eastern Kentucky. Without further testing, flat, highly compacted, surface-mined sites should be avoided. These data also show that environmental support in the form of tree shelters and soil amendments was required to ensure adequate initial survival of float tray seedlings. Results showed an initial seedling survival rate of < 25 percent

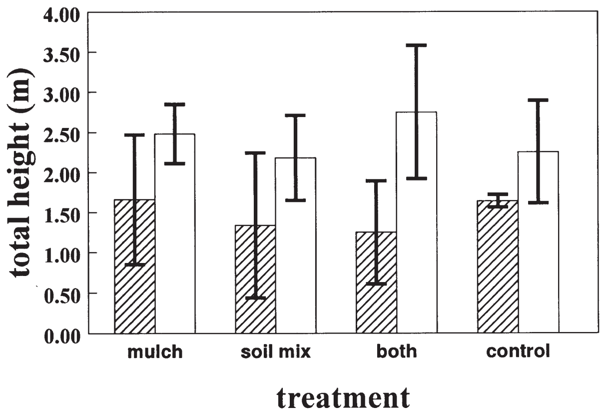

Figure 4—Total height of 2-year-old *Paulowina tomentosa* float tray seedlings growing on a south facing surface-mined site in eastern Kentucky. Bars (open=sheltered seedlings and lined=nonsheltered seedlings)and standard error bars represent data within one site.

when planted without environmental support, regardless of site. Survival was improved significantly on all sites with the use of 1-foot-tall tree shelters and a soil amendment with a number of sites having > 80 percent survival. However, shelters and the soil amendment treatments had limited effect on long-term height growth. While the sites used in this study were in eastern Kentucky, the wide range of site qualities and rooting media involved in this study suggest that the recommendations developed from this study may have broad application.

ACKNOWLEDGMENT

This research was supported by the McIntire-Stennis Cooperative Forest Research Program and the University of Kentucky Cooperative Extension Service. The paper is publication 97-09-36 of the Kentucky Agricultural Experiment Station. The author would like to thank staff at the University of Kentucky's Robinson Forest for field sites and maintenance and Western Pocahontas Properties for funding and field sites. A special thanks to Scott Shouse, Chris Harney, John Jackson, Jason Riggins, and Gene Keith Hilpp for field assistance.

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USE OF COVER CROPS IN SHORT-ROTATION HARDWOOD PLANTATIONS

R.K. Malik, T.H. Green, G.F. Brown, and V.R. Tolbert[1]

Abstract—This study investigates the effects of cover crops on the growth and biomass yield of sweetgum (*Liquidambar styraciflua* [L.]) planted as a short-rotation woody crop at a 1.5 by 3 meter spacing. Four cover crops, winter rye grass (*Lolium multigeonum* L., a winter annual grass); tall fescue (*Fescuta eliator* L., a growing-season perennial grass); crimson clover (*Trifolium incarnatum* L., a winter annual legume); and interstate sericea (*Lespedeza ameata* L., a growing-season perennial legume), were tested at two different strip widths (1.22 and 2.44 meters) as well as a control with complete competition control. Height and ground-line diameter of trees were measured on a monthly basis. The cover crops and strip widths significantly affected height, ground line diameter, and volume index of sweetgum. Lespedeza and tall fescue significantly affected ground-line diameter, height, and volume index over rye and control. Crimson clover significantly affected ground-line diameter over control and volume index over rye grass and control. Rye grass and control were not significantly different from each other. Sweetgum ground-line diameter, height, and volume index were significantly affected by the strip widths. The greatest reduction was at the 2.44 meter (8 feet) strip width. The reduction in diameter and volume index by strip width was more significant than for height.

INTRODUCTION

Hardwoods are preferred over pines as short-rotation intensive culture (SRIC) species because of their rapid juvenile growth rates and ability to coppice. Unlike conventional forestry, individual tree size and form are not a major consideration for SRIC. More important factors are initial survival, rapid early growth rates, high annual energy and biomass yields, coppice survivability, and subsequent vigor. For these reasons and because the species is adaptable to many sites, sweetgum has become an important species considered for SRIC management. Sweetgum (*Liquidambar styraciflua* L.) is one of the most important commercial hardwoods in the southeast and is put to a great many uses such as lumber, veneer, plywood, slack cooperage, railroad ties, pulpwood and fuel (USDA 1974).

Biomass resources have been historically important for energy supplies. They offer an excellent renewable alternative to fossil fuels. The biomass resources include agricultural residues, long-rotation woody plantings, thinning material, logging residues, wood wastes and residues from production of paper and forest products, and specialized wood and herbaceous crops developed specifically for energy production (Hohenstein and Wright 1994). The overall energy use has increased by 167 percent during 1949 to 1990, wood energy use has increased by 108 percent, while wood energy use represents 82 percent of the total biomass energy use (U.S. DOE 1993).

The research on wood energy-crops is leading forestry into a new era of more intensive silviculture because there will be a greater need for large, renewable woody biomass plantations for conversion to gasoline and gaseous fuels. The wood consumption of a biomass conversion facility will be in the range of 200,000 to 1 million dry megagrams per year (1 megagram = 1 metric ton = 1.1 English tons), similar to the demand of a pulp mill (Ranney and others 1987). Under such a scenario, intensive culture of hardwoods appears to fit this need very well (Farnum and others 1983).

The high-yield biomass energy crops could be produced on most of the U.S. land currently under food crops production. The Department of Agriculture reported 162 million hectare (Mha) of cropland in the United States in 1991. Out of this base, 137 Mha were either used to produce crops, were planted but not harvested, or were summer fallowed. The remaining 25 Mha were idled either through Annual Acreage Reduction programs or through Conservation Reserve Program (U.S. DOE 1991).

The short-rotation intensive culture (SRIC) hardwoods are presumed to protect soil exceptionally well after first growing season. Under SRIC conditions, mean annual rate for productivity of 12 to 16 megagrams per hectare (5.4 to 7.1 tons per acre) is considered an acceptable range. Eventually, a goal of up to 20 dry megagrams per hectare (about 9 tons per acre) may be achieved. SRIC crops would be an excellent compromise for obtaining economic returns from the Conservation Reserve Program (Food Security Act, 1985) land while providing needed soil protection as well (Ranney and others 1987). Hardwood SRIC is not feasible without good weed control, which is usually accomplished through agricultural-type site preparation and herbicide use until canopy closure (Kennedy, 1984).

The objective of this study was to determine the feasibility of cover crops use for erosion protection during the early phase of stand development. The study examined both erosion protection and sweetgum growth reduction by various cover crop regimes. This paper is concerned only with the effects of cover crops on sweetgum growth.

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METHODS

Site Description

The experiment was established at the Winfred Thomas Agricultural Research Station in Hazel Green, AL, 9 miles north of Alabama A&M University campus. The soil is classified as a Decatur and cumberland silt loam, undulating phases, with 2 to 6 percent slope with good natural drainage. The site has previously been occupied by corn cultivation. Each plot measures 21.34 meter by 7.62 meter (65 by 25 feet) separated by a 3.05 meter (10 feet) buffer. Each plot is surrounded by a 20 to 25 centimeter (8 to 10 inch) high soil berm. There are nine plots in each of three replications.

Cover Crops and Sweetgum Planting

The four types of cover crops planted are: (a) winter annual - rye grass (*Lolium multigeonum* L.) variety Kino seeded @ 25 pound per acre + wheat (*Triticum aestivum* L.) @ 40 pound per acre, (b) perennial grass - tall fescue (*Fescuta eliator* L.) variety Kentucky 31 seeded @ 15 pound per acre + Wheat (*Triticum aestivum* L.) @ 40 pound per acre, (c) winter annual legume - crimson clover (*Trifolium incarnatum* L.) variety Big bee seeded @ 25 pound per acre (all three planted on November 3, 1994), and (d) perennial legume -interstate sericea (*Lespedeza ameata* L.) variety seeded @ 30 pound per acre (planted on May 17, 1995). The cover crop strip widths between sweetgum rows were maintained at 1.22 meter (4 feet) and 2.44 meter (8 feet) as well as a control with no cover crop. One-year-old seedlings of sweetgum were transplanted as a short rotation woody crop on March 21 to 27, 1995 at 1.5 by 3.0 meter (5 by 10 feet) spacing with 35 sweetgum plants in each plot, 315 plants per replication, and 945 plants in three replications.

Measurements

For the first 2 years of plant growth, monthly measurements of height and ground-line diameter (gld) were recorded from May to September 1995 and 1996, with dormant period information as of February 1996, to compare plants performance under different cover crop regimes.

Study Design and Data Analysis

The experiment in a Split Plot design with one level of nesting. The cover crops per plot are the main treatments, cover crop's strip width treatments are split with 15 trees nested. The data were analyzed using the GLM procedure of Statistical Analysis System for analysis of variance and means separated by Tukey's Studentized Range Test.

RESULTS AND DISCUSSIONS

Effects of Cover Crops

Ground line diameter—The ground line diameter (gld) was significantly affected by the cover crops. Rye grass was not significantly different from control. The crimson clover, lespedeza, and tall fescue significantly reduced gld in comparison to the control. Among cover crops, crimson clover and rye grass were not significantly different, similarly crimson clover, lespedeza, and tall fescue were not significantly different from each other; however, both lespedeza and tall fescue were significantly different from rye grass. The highest gld was observed under control, followed by rye grass, crimson clover, tall fescue, and lespedeza (table 1). Gld was affected early in the first year, becoming statistically significant by July of the first growing season (fig. 1). At this time, crimson clover had significantly reduced gld compared to control. Crimson clover continued to be the only cover crop to significantly reduce gld throughout year 1.

Table 1—Effects of cover crops on sweetgum during the growing seasons of 1995 and 1996[a]

Sr. no., year, and cover crop	Ground line diameter	Height	Volume index (D2H)
	- - - - - - - *cm* - - - - - - -		- - - *cm3* - - -
First growing season			
(1) Control	2.30a	100.86a	551.88a
(2) Crimson clover	1.84b	93.45a	343.62b
(3) Rye grass	2.14a	98.03a	468.13ab
(4) Lespedeza	2.06ab	101.41a	454.73ab
(5) Tall fescue	2.14a	103.80a	488.12ab
Second growing season			
(1) Control	4.64a	201.34a	4430.07a
(2) Crimson clover	3.99bc	190.51ab	3219.37b
(3) Rye grass	4.30ab	199.56a	3782.06a
(4) Lespedeza	3.78c	173.00c	2629.44c
(5) Tall fescue	3.84c	180.29bc	2783.40bc

[a] Means (year-wise) within same column effects followed by the same letter are not significantly different at 5 percent level.

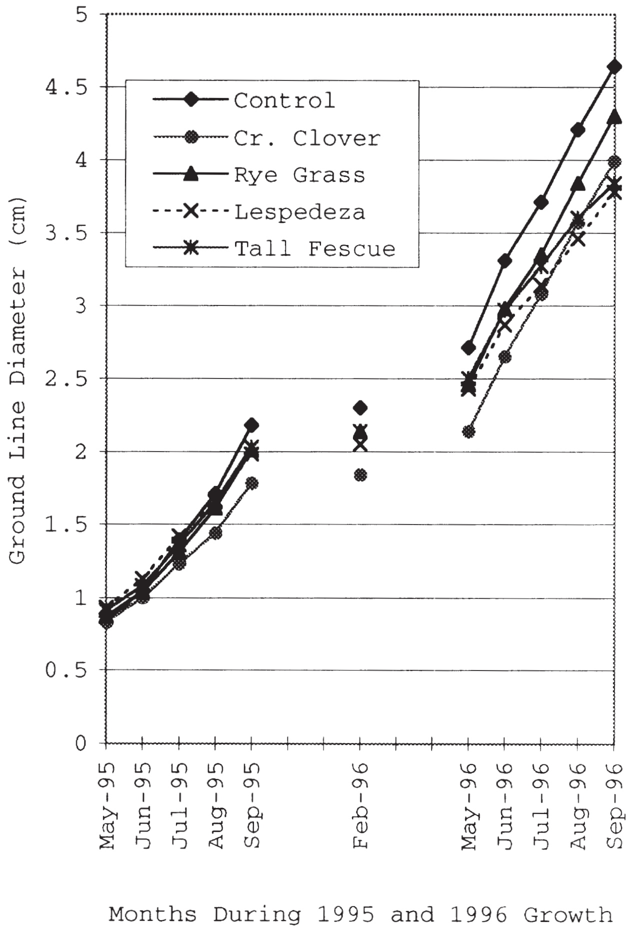

Figure 1—Effects of cover crops on sweetgum ground-line diameter.

Winter annual cover crops tended to reduce growth to a greater extent than perennial cover crops during the first year. During the second growing season, however, this relationship changed. Both tall fescue and lespedeza exerted a greater growth reduction than clover or rye grass. The effect increased throughout the growing season and by the end of the growing season the gld curves for trees grown with perennial cover crops were diverging from the rest. These results indicate that winter annual cover crops exert their greatest influence on sweetgum growth during their first year, whereas growing season perennials take longer to influence growth. This may be due to the early effects of the winter annuals during the first year after planting. Because these cover crops were already well established when the trees were still undergoing planting shock, competition by these crops resulted in greater growth reduction.

Using legumes as cover crops did not increase gld over grasses during the first growing seasons. This indicates that benefits of the legumes, by way of fixing nitrogen into soil, did not result in any increase in growth. Apparently, competition for moisture during first 2 years of growth was the dominant competitive effect of cover crops.

Height—The height of trees with crimson clover and rye grass was not significantly different than control; however, lespedeza and tall fescue were significantly lower from control. Among cover crops, crimson clover and rye grass were not significantly different, the crimson clover and tall fescue were not significantly different, similarly lespedeza and tall fescue were not significantly different from each other. However, both lespedeza and tall fescue were significantly different from rye grass. The maximum height was recorded under control, followed by rye grass, crimson clover, tall fescue, and lespedeza (table 1). No significant differences were observed during the first year of growth (fig. 2). Height first became significant in the second growing season, and rye grass was not significantly different from control. Lespedeza and tall fescue were not significantly different, but are significantly different from control and rye grass (fig. 2).

Volume index—The volume index closely paralleled diameter growth. The rye grass and control were not significantly different. The crimson clover, tall fescue, and lespedeza were significantly different from control. Among cover crops, the crimson clover and tall fescue were not significantly different, similarly lespedeza and tall fescue were not significant; however, crimson clover, lespedeza, and tall fescue were significantly different from rye grass. Crimson clover and lespedeza were also significantly different. The highest volume index was observed with control, followed by rye grass, crimson clover, tall fescue, and lespedeza (table 1). A review of fig. 3 reveals that at the end of the second growing season the volume index curves resulting from each cover crop are diverging.

Effects of Strips Widths

Ground line diameter—Gld first became statistically significant in August of the first growing season (fig. 4). Both strip widths became significantly different from

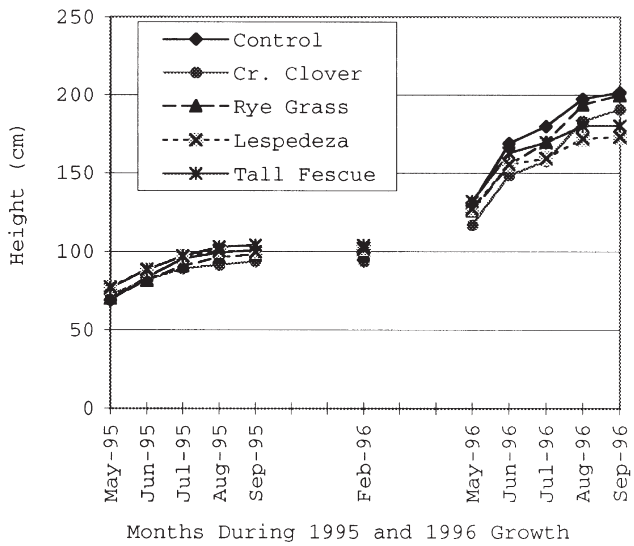

Figure 2—Effects of cover crops on sweetgum height.

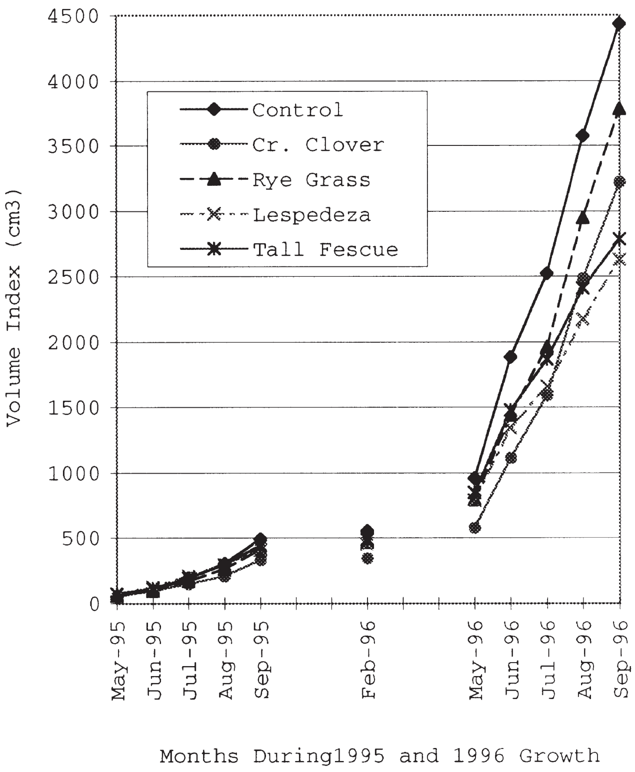

Figure 3—Effects of cover crops on sweetgum volume index.

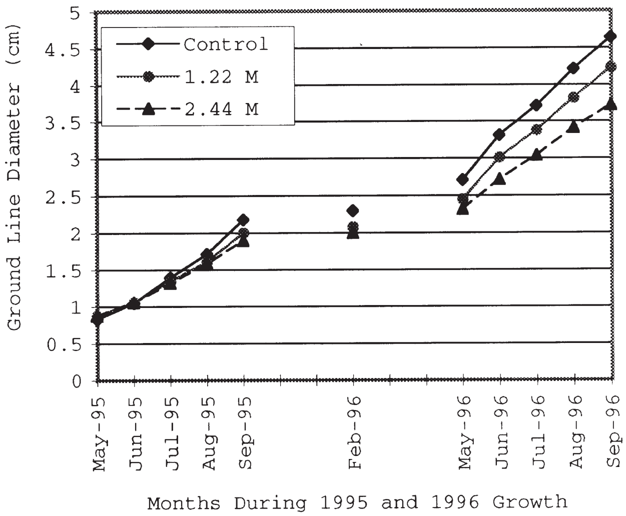

Figure 4—Sweetgum ground-line diameter affected by strip width of cover crops.

control during the first growing season. This relation became more apparent during second growing season when 1.22 meter (4 feet), 2.44 meter (8 feet) and control became statistically different from each other beginning early second growing season (fig. 4). Maximum gld was suppressed by 2.44 meter (8 feet) strip width, followed by 1.22 meter (4 feet) and control.

Height—The height was not significantly affected by strip widths during the first growing season (table 2). However, during the second growing season 2.44 meter strip width significantly reduced height over both 1.22 meter strip width and control (table 2). The height for the first time became statistically different in June 1996, and onwards, the same may be seen from diverging graph lines in fig. 5.

Volume index—The volume index was significantly affected by strip widths of cover crops. Volume index was not found to be significant during the first growing season (table 2). The volume index was, however, observed as significant for the first time early second growing season, when all the three strip widths were observed to be significantly different from each other, and this trend was maintained (fig. 6).

CONCLUSION

Sweetgum growth was significantly affected by all cover crops and at each strip width. During the first growing season, winter annual cover crops tended to reduce growth more than perennial. This trend, however, was reversed during the second growing season. The perennial cover crops showed increased growth reduction during second growing season. The legumes did not benefit sweetgum over grasses and, in fact, reduced growth to a greater extent than grasses.

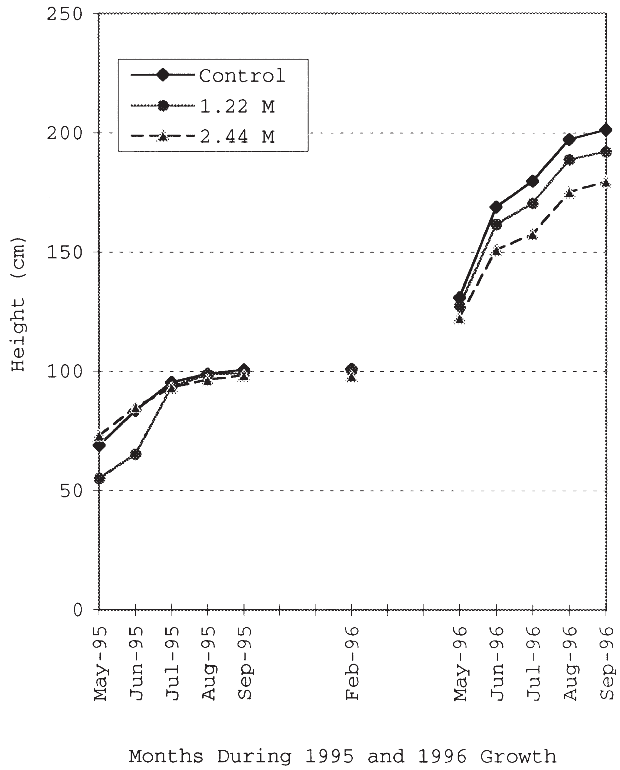

Figure 5—Sweetgum height affected by strip width of cover crops.

Table 2—Effects of strip widths of cover crops on sweetgum during the growing seasons of 1995 and 1996[a]

Sr. no., year, and cover crop	Ground line diameter	Height	Volume index (D2H)
	- - - - - - - *cm* - - - - - - -		- - - *cm3* - - -
First growing season			
(1) Control (no cover)	2.30a	100.86a	551.88a
(2) 1.22 meters	2.08b	100.37a	462.48a
(3) 2.44 meters	2.00b	97.99a	415.07a
Second growing season			
(1) Control (no cover)	4.63a	201.34a	4430.34a
(2) 1.22 meters	4.23b	192.15a	3559.47b
(3) 2.44 meters	3.72c	179.53b	2646.52c

[a] Means (year-wise) within same column effects followed by the same letter are not significantly different at 5 percent level.

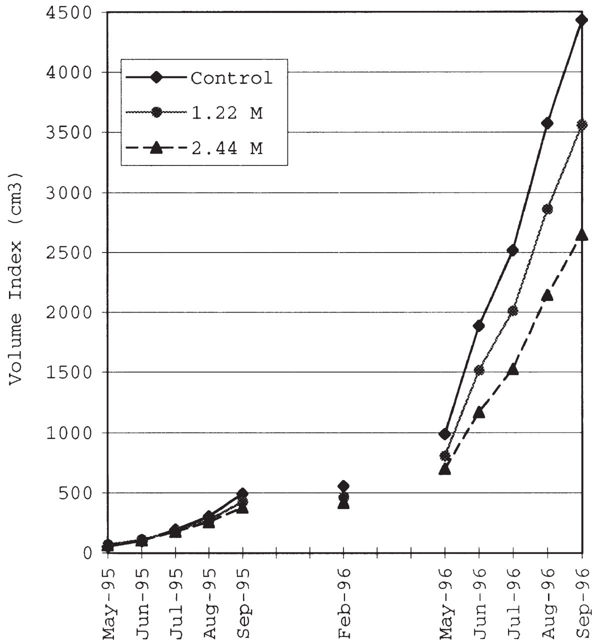

Figure 6—Sweetgum volume index affected by strip width of cover crops.

With regard to strip widths, these data show that the narrower the cover crop strip (wider the competition-free zone around the sweetgum rows) the better the growth of sweetgum trees. In this study, the 1.22 meter strip width, which provided 0.92 meter of competition-free area on each side of the sweetgum trees, still caused a competition-induced reduction in sweetgum growth. However, this growth reduction was less significant than that using wider cover crop strips.

ACKNOWLEDGMENT

The research is supported by the Biofuels Feedstock Development Program, Oak Ridge National Laboratory, Oak Ridge, TN.

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EFFECT OF SEEDLING SIZE AND FIRST-ORDER-LATERAL ROOTS ON EARLY DEVELOPMENT OF NORTHERN RED OAK ON MESIC SITES

Paul P. Kormanik, Shi-Jean S. Sung, Donald J. Kass, and Scott Schlarbaum[1]

Abstract—Northern red oak (*Quercus rubra*) seedlings were placed in three grades based on number of first-order-lateral roots. The grades were poor, medium, and good and had numbers of 0 to 6, 7 to 11 and ≥ 12, respectively. Eighty seedlings from each group were either underplanted or established in an adjacent clearcut on a high-quality mesic site in North Carolina. There were 240 seedlings outplanted on each area. The poor-graded seedlings were initially smaller than the medium and good seedlings with heights and root collar diameters of about 67 centimeters and 7.4 millimeters; 115 centimeters and 11.3 millimeters; and 138 centimeters and 13.4 millimeters, respectively. Survival was better overall with the underplanted seedlings at year 7, with the poor, medium, and good seedlings surviving at 75, 78, and 96 percent, respectively. Growth was unsatisfactory for all three grades. Survival on the clearcut was affected by a 17-year-locust (*Magicicada septendecim L.*) infestation and heavy stump sprout competition. Survival of the poor, medium, and good seedlings were 59, 63, and 66 percent, respectively. Height and stem caliper were very good for the medium and good seedlings. Only 3 seedlings from the 0-6 grade were free to grow at age 5, while 29 of the seedlings in the good grade were free to grow.

INTRODUCTION

Scores of manuscripts have reported on attempts to obtain northern red oak (*Quercus rubra*) regeneration on desirable mesic sites where the species is an important economic and ecological component of the forest. The basic tenets of most of this northern red oak research have been reported by Sanders (1971, 1972; Sanders and Graney 1993). That is, for this species to be a significant component of a future stand, they must be represented by specific numbers and size classes in the understory when the current stand is harvested. Stand structure is regulated by thinning of either (or both) the canopy and the understory to encourage the establishment and development of the smaller oak regeneration before the residual stand is harvested (Loftis 1983, 1990). Many of the regeneration attempts that have shown promise of providing adequate oak regeneration are on the more xeric sites, where northern red oak may not be the desirable oak species. Stable oak communities are not difficult to obtain or to maintain on xerophytic sites where site index is ≤60 (base age 50) (Lorimer 1993).

Kellison (1993) reported that obtaining oak regeneration is not a universal generic problem but, rather, is a specific problem of northern red oak on high-quality mesic sites. This serious problem is complicated by ignoring the effect of edaphic and environmental factors on the competitor species of this important oak species. The pertinent issue may be the desire to develop a generic management protocol that is simultaneously politically correct, scientifically sound, and universally applicable to all *Quercus* species regardless of edaphic and environmental constraints. This "Holy Grail" is unlikely to exist and if research and management continues to search for it, then Kellison's (1993) prediction of northern oak becoming the "California Condor" of the eastern deciduous forest may indeed become a reality.

Natural versus Artificial Regeneration

Oak research at the Institute for Tree/Root Biology (ITRB) was initiated a decade ago when we began screening northern red oak open-pollinated, half-sib progeny for first-order lateral roots (FOLR) development. The ultimate purpose of the research was to develop a seedling grading system to be used for assessing the future competitive ability of individual outplanted seedlings. We first had to develop a nursery protocol to grow high quality seedlings of this species, since a consistently reliable method had not been reported for any species of oak (Williams and Hanks 1976). Only a few organizations were even considering an option of artificially regenerating northern red oak because emphasis was on natural regeneration. The primary management emphasis was on mensurational aspects of stand manipulation, such as timing of thinning or removal of overhead canopy, rather than on the biological requirements of the species. (Loftis 1990, Johnson and others 1989).

Timing of regeneration cuts for northern red oak is difficult because of the periodic occurrence of good seed years and reduced acorn crop as the stand ages and passes its peak reproductive years. However, following a good seed year on most sites, small newly germinated northern red oak seedlings can be found in great numbers for several years (Loftis 1990). Few of these will survive on mesic upland sites for sunlight is usually significantly lower than the compensation point required by northern red oak seedling (Hodges and Gardiner 1993). Similar reliance on periodic acorn crops for seedling production in nurseries severely limits artificial enrichment planting opportunities that should accompany natural regeneration. Absence of a ready source of acorns has severely limited planned research on this species but recent results on acorn production from seed orchards have been encouraging.[2]

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Development of Northern Red Oak Seedlings

We will not include a discourse on acorn production but will assume the acorn has germinated. After germination, seedlings may survive a few years but light intensity near the forest floor on mesic sites is often below the compensation point for northern red oak. Seedlings seldom develop more than 2 or 3 leaves and the terminal buds remain very small. However, because of small openings in the canopy and sporadic understory, individuals can survive for a number of years under these suboptimal light conditions. They frequently break bud several weeks before canopy closure and may be able to partially replenish root reserves depleted during bud break. Although complete information is lacking, those seedlings reaching more than 1 meter in height might be considered advanced reproduction that can benefit from partial release. These partially released trees may develop slowly and after 9 years have a basal diameter increase of 0.86 centimeter with insignificant height growth (Loftis 1990). Thus, before as well as after this release, growth is far from satisfactory and newly germinated species like yellow poplar (*Lirodendron tulipfera*) or the already established competing vegetation rapidly overtops all but the tallest of the slower growing northern red oak seedlings. However, northern red oaks are notoriously slow to respond to initial release, and the heavy competition on mesic sites is far more severe than on the xeric sites. Thus, initial clearcutting or a series of release and regeneration cuts to release this species may be unsatisfactory as long as the reproduction is being overtopped.

The purpose of this study was to determine how large northern red oak seedlings stratified by FOLR numbers react to competition in a clearcut and an understory planting on a high-quality mesic site.

METHOD

Two adjacent areas on the USDA Forest Service's Grandfather Ranger District on the Pisgah National Forest, 12 miles northwest of Marion, NC, were used in this study. The site index for yellow poplar was approximately 100 (base age 50). The main crown canopy was a mixture of northern red oak, white oak (*Q. alba*), red maple (*Acer rubrum*) and yellow poplar. The clearcut area to be used for enrichment planting was a small segment of a larger harvested area.

The area to be underplanted was immediately across the road and consisted of the same species composition as the clearcut area. For the underplanting, basal area was reduced by 30 percent to 20.44 square meters per hectare (88 square feet per acre) primarily by removing the intermediates and suppressed trees from the canopy level as well as those individuals occurring in the subcanopy level.

Acorns were collected from the Forest Service's Wataqua seed orchard in eastern Tennessee. The seedlings were grown at the ITRB Whitehall Experimental Nursery during the 1989 growing season, using the hardwood nursery protocol reported elsewhere (Kormanik and others 1994a). The seedlings were harvested during February 1990 and outplanted in March 1990.

When lifted, the seedlings were placed in one of three groups, poor, medium, and good, based upon FOLR numbers. FOLR numbers were defined as roots with basal diameter exceeding 1 millimeter along the first 30 centimeters below the root collar. The poor, medium, and good groups had FOLR numbers of 0 to 6, 7 to 11, and $\geq$ 12, respectively. Root collar diameters (RCD), and heights, were recorded for each seedling. Each lateral root was trimmed to approximately 13 centimeters and taproots were pruned to 30 centimeters before seedlings were outplanted.

Eight blocks were laid across the contour and 10 trees from each grade were shovel planted at 1.5 meters by 3.1 meters spacing in adjacent rows. The design was a split-split plot with eight blocks. Each block contained 10 trees from each grade, giving a total of 240 seedlings per treatment. The spacing was maintained with only minor adjustments. All standing trees in the clearcut area were felled before planting but no subsequent vegetation control measures were taken. Mechanical control in the underplanting area removed subcanopy trees as well as trees overlapping naturally regenerated northern red oak seedlings. Essentially no subcanopy remained after basal area reductions had been completed.

Survival data were obtained after the first growing season in 1990. Survival, RCD, and HGT were also obtained after the fifth year (1994). Competing vegetation density was recorded from three positions in each block during the fifth-year remeasurement. Five artificially regenerated trees were excavated after the fifth growing season from both the clearcut and underplanting areas to examine root development characteristics. Survival, diameter at breast height (d.b.h.), and heights were also obtained after the seventh growing season (1997).

RESULTS AND DISCUSSION

Two unanticipated factors significantly affected the results. The first was a massive infestation of the 17-year locust (*Magicicada septendecim L.*) that severely damaged almost all 240 seedlings in the clearcut toward the end of the second growing season. Very few naturally regenerated or coppiced trees were affected in the clearcut and none of the oak seedlings in the understory planting were attacked. The second factor was that the intense competition from untreated stumps of Carolina silverbell (*Halesia carolina*), red maple, and yellow poplar seedlings proved to be more significant than anticipated.

Seedling Survival

Survival following the first season was 100 percent in both the clearcut and understory plantings for all three FOLR groups of seedlings. The second year, locust damage was so extensive on seedlings in the clearcut that their long-term survival appeared to be in doubt. Many stems were severely damaged over half to two-thirds of their heights by the end of the second growing season. In the understory, all seedlings from all three FOLR grades were intact (table 1). A total of only 20 trees had not survived in the understory at age 5. Of these 20, 16 were in the poor (0 to 6) FOLR group, two in the medium (7 to 11) group, and two

Table 1—Northern red oak survival by first-order-lateral root groupings[a] from clearcut and understory plantings

Survival rate	Clearcut			Understory		
	Good	Medium	Poor	Good	Medium	Poor
1st year	100	100	100	100	100	100
5th year	68	66	63	96	96	96
7th year	66	63	59	96	78	75

[a] Good = ≥12; medium = 7-11; poor = 0-6.

in the good (≥12) group. When stands were remeasured after the seventh growing season, more mortality had occurred in both the medium and poor FOLR grades but essentially all in the good grades were still surviving in the understory (table 1).

Mortality in the clearcut was more severe (table 1) due to the result of both the intense competition from stump sprouts and the residual effect of the locust damage. Survival did not change between the fifth and seventh year in the clearcut planting area.

Growth, Vigor, and Competitive Status of Regeneration

Most of the naturally regenerated oak seedlings were less than 30 centimeters tall when the study was initiated and few of these were found by age 7. Although we did not make an exhaustive survey, newly developed seedlings were rarely observed. We do not know whether this situation occurred due to limited mast production or insufficient sunlight for seedling development. In neither the understory planting nor the clearcut area, would natural northern red oak regeneration development have been sufficient to be more than a minor component on this high-quality mesic site. Artificial regeneration, however, has altered this possibility through at least age 7.

Underplanting

The original basal area reduction has been effective through the seventh year, in that no low or mid-crown canopies have developed. However, even the best FOLR grade seedlings have not developed satisfactorily. Height growth has been minimal and RCD increases through the fifth year have remained essentially unchanged from their initial caliper; the seventh year d.b.h. measurements are tracking that of the RCD development (figs. 1A, 1B). The poor (0 to 6) FOLR group of seedlings remains the smallest and is spindly, although some—those taller than 1.0 meter—might be considered “advanced” reproduction. Characteristic of all underplanted seedlings, regardless of FOLR grade, is that only a few leaves develop annually. Even on the largest seedling, we have seldom observed more than 20 to 30 leaves. Tip dieback has occurred several times on most of the seedlings and is not associated with any particular FOLR grade. Low vigor of the poor and medium FOLR grades appeared to be related to the mortality that occurred between the fifth and seventh year. The seedlings within a specific grade were uniform in size and appear to be related to their initial sizes.

Trees excavated after year 5 showed that FOLR numbers had declined for each seedling examined. This was relatively unexpected. Underplanting or shelterwood regeneration assumptions are that the released seedlings will develop a vigorous root system and be competitive when the stand is harvested. As reported in other species, unfavorable edaphic or environmental conditions such as low light intensity can result in a reduction in FOLR numbers and vigor with a preferential carbon allocation to the taproots at the expense of the lateral roots (Sung and others 1996; Kormanik and others 1994b; Sung and other, in press). This may be the situation here since photosynthetic active radiation was at least 1500 $\mu E/m^2/s^2$ in the original clearcuts but less than ca. 5 percent in the understory.[3]

At age 7, the mean height increases since underplanting for the good, medium, and poor FOLR grades were 50, 40, and 30 centimeters, respectively (fig. 1A). The tallest seedlings were 280, 200, and 170 centimeters for each FOLR grade, respectively. In the understory, FOLR grades had little effect upon RCD increments through the fifth year and the poor FOLR grade had few seedlings large enough to obtain d.b.h. measurements at the seventh year (fig. 1B).

Clearcut

Large differences were observed in all growth parameters among FOLR root grades in the clearcut area. Survival was not related to root grade and seedling size per se. All seedlings remained free to grow during their first year, but competition for sunlight became intense between years 2

[3] Data on file at the USDA Forest Service, Institute for Tree/Root Biology, Athens, GA 30601.

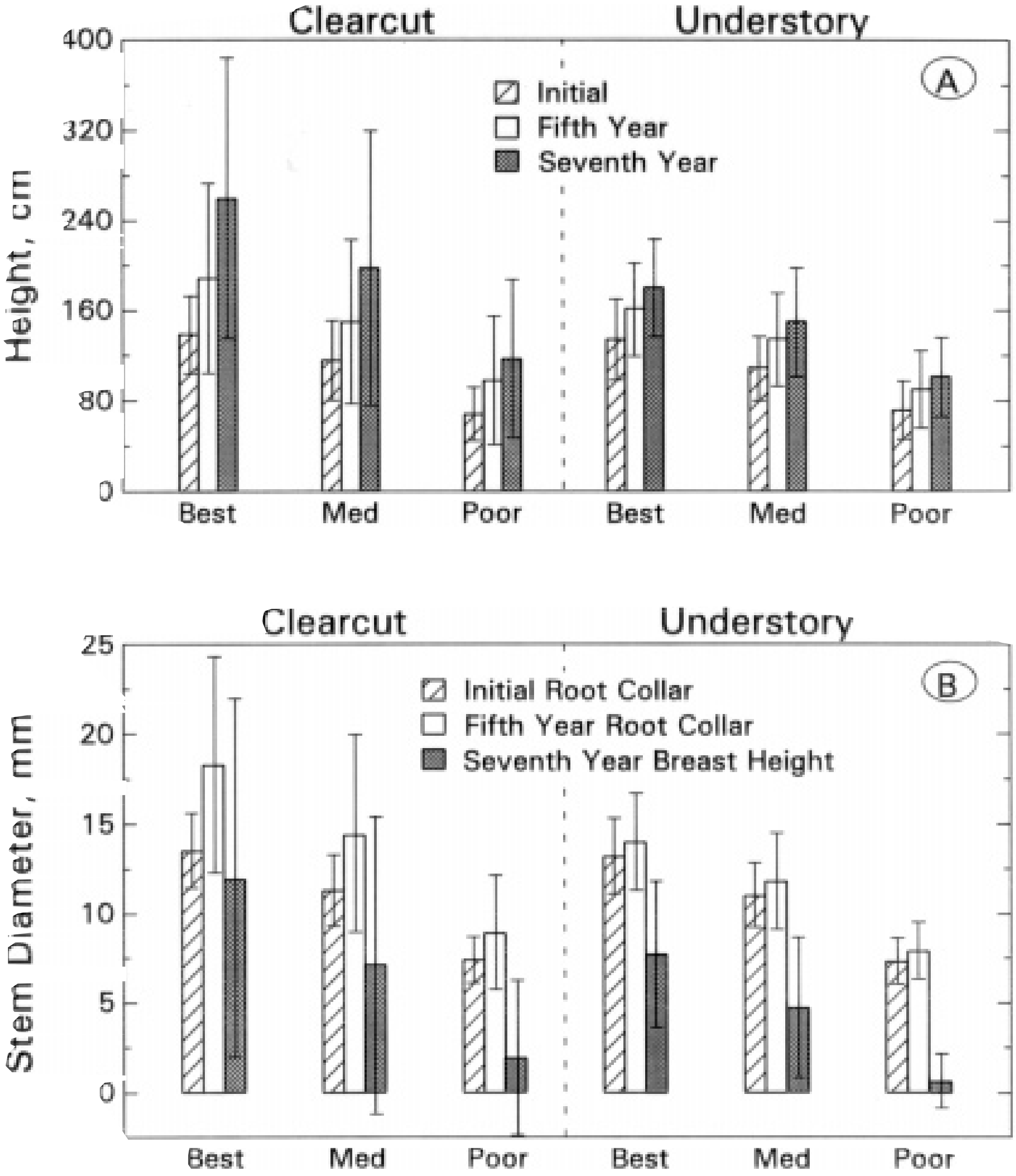

Figure 1—Initial-, fifth-, and seventh-year diameters and heights of root graded (Good = ≥12 first-order-lateral roots; medium =7-11 first-order-lateral roots; poor = 0-6 first-order-lateral roots) northern red oak in a clearcut and adjacent underplanting. Figure 1A heights; 1B diameters.

and 5 as stump sprouts and other seedlings rapidly developed. When the first remeasurement was made at year 5, evidence of significant dieback of many stems was clearly visible as a direct result of the second growing season attack by the 17 year cicada. At age 5, seedling sizes and competitive position were closely related to original FOLR grade, with the poorest grade trailing far behind the better two grades (figs. 1A, 1B). At that time, only 3 seedlings were free to grow in the poor grade, but 15 of the medium and 29 of the best grade were in this category. This latter number, 29, is especially significant as it represents about 50 percent of the surviving seedlings in this good FOLR grade. The tallest seedlings at ages 5 and 7 were strikingly different for each FOLR grade. At age 5, the poor, medium, and good FOLR grades' tallest seedlings were 235, 455, and 510 centimeters, respectively (see footnote 3). Only the medium and good grades continued to be free to grow at age 7. Many were beginning to experience severe competition from the faster growing Carolina silverbell and yellow poplar seedlings, and red maple sprouts.

At age 5, a thorough survey of competition in the clearcut revealed that the planted oaks were competing with 126,800 stems per hectare of 14 different deciduous hardwood species. However, it was the sprouts of the three above-mentioned species and the yellow-poplar seedlings that had become the major competitors and had affected oak development the most. Vegetation was not resurveyed at age 7, but stem numbers did not appear to have declined from age 5.

During the seventh year, when crown competition in the clearcut area became intense, the number of leaves on the oak seedlings was quite high with 200 to 400 leaves being common on the better seedlings. The effect of leaf number was most evident during the initial 3 years when essentially all larger seedlings were free to grow. Northern red oak seedling development during the first 2 to 3 years is especially important and is dependent upon full sunlight for optimum establishment. We found that during years 1 and 2, major carbon allocation with northern red oak is directed to root maintenance and development with little stem elongation occurring. Without early establishment of an adequate root system, subsequent top growth is severely restricted and newly released or outplanted seedlings are soon overtopped.

Many of the naturally regenerated oak seedlings had died or had been suppressed by faster growing competitors between years 2 and 7. The reason is clear for this mortality and what was observed in this study is probably true on other mesic sites. The established oak seedlings did not immediately respond to release and few seedlings produced more than 3 to 5 leaves the first or second year. Growth during this first year was negligible as others have reported (Pope 1993). Newly germinated herbaceous vegetation, other tree species, and many sprouts soon overtopped these naturally regenerated northern red oak seedlings. By the second growing season, most of these naturally regenerated seedlings were completely overtopped and received phtosynthetic active radiation of less than 5 percent of full sunlight.

The large artificially regenerated seedlings essentially remained free to grow until the third and fourth years except when planted adjacent to stumps that sprouted vigorously. During this early period, the surviving seedlings developed a large root system that was not observed in underplanted individuals. The advantage of the large seedlings was quite obvious. The newly germinated competitors started at ground level and they seldom were more than 60 to 80 centimeters tall the first year. This was well below the height of the medium and good planted oak seedlings. Even the stump sprouts resulted in minimal competition during years 1 and 2 when the artificially regenerated oaks were establishing their root system. Thus, an early major, limiting factor of northern red oak characteristically encountered on high-quality mesic sites was moderated, i.e., access to full sun. However, it is expected that at least one release will be needed to sustain development of these free-to-grow individuals.

CONCLUSION

Large northern red oak with FOLR numbers ≥7 can be used effectively for enrichment planting on high-quality mesic sites following clearcutting. Large seedlings effectively compete against severe competition from newly germinated seedlings and other herbaceous vegetation, but by age 7 may need release from the more rapidly growing stump sprouts and yellow poplar seedlings. Planting immediately adjacent to untreated stumps of yellow-poplar, red maple, and Carolina silverbell can result in severe competition and mortality. Few individuals from the poor FOLR grade (0 to 6) were in a competitive position after year 2. Treatment of stumps adjacent to artificially regenerated seedlings may prove beneficial but was not tested.

Underplanted individuals released to a basal area of 20.44 square meters per hectare had a better survival rate than those in the clearcut, but grew little during these first 7 years. The seedlings repeatedly died back regardless of initial sizes and FOLR numbers. Excavation at age 5 from the understory, revealed most of the original FOLR have senescenced and root mass was smaller than when initially outplanted due to mortality of the FOLR.

Neither artificial nor natural regeneration techniques may prove effective for regenerating northern red oak on mesic sites unless mechanical or chemical competition control accompanies use of large nursery-grown seedlings. It is questionable whether advanced natural regeneration can be relied upon on mesic sites with the shelterwood method of regenerating this species.

ACKNOWLEDGMENT

This research was funded partially by the Department of Energy and USDA Forest Service, Region 8.

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PREHARVEST HERBICIDE METHOD TO DEVELOP COMPETITIVE OAK REPRODUCTION IN UPLAND OAK STANDS OF THE MOUNTAINS AND PIEDMONT OF NORTH CAROLINA—7-YEAR RESULTS

Donald J. Kass And Warren G. Boyette[1]

Abstract—To promote development of small advanced upland oak reproduction, two variations of understory and midstory basal area reduction were applied to medium quality sites (site index 70 to 80) of mixed oak stands in the piedmont and mountains of North Carolina. Seven-year measurements indicate some increase in survival, diameter, and heights in the treated plots as compared to the untreated plots. However, in practical terms, the slight increases in diameter are not enough to increase the likelihood that the oak seedlings would be competitive should these stands be harvested now. More time will be required on medium-quality sites for the small oaks to develop to a larger size. This extended timeframe may be a serious obstacle to implementation of the practice by the private landowner.

INTRODUCTION

Once harvested, upland oak stands on medium and good sites are not regenerating to a viable component of oak species. The upland oak resource is widespread and valuable, especially for timber and wildlife. Any technique or practice that shows promise of enhancing the oak regeneration component is needed. A large number of advanced, well-developed oak seedlings are usually required to ensure adequate regeneration (Sander and Clark 1971, Johnson 1975, Loftis 1983). An Oak Shelterwood method for the mountain cove sites seems to develop large, advanced, northern red oak regeneration on very good sites (Loftis 1990b, 1992). It is important to determine whether this method works as well on medium-quality sites, which are common in the piedmont and mountains.

In this study, two variations of basal area reduction were applied to mixed oak stands on medium quality sites in the piedmont and mountains of North Carolina. The purpose of the study was to: (1) compare the effectiveness of the oak shelterwood and another silvicultural technique in advancing small upland oak reproduction to a larger, competitive size; and (2) determine the rate of small oak reproduction development, by species, following treatment.

METHODS

Three stand treatments were utilized in the study.

(1) Control. No treatment.
(2) Oak Shelterwood. Kill the understory and midstory and, if necessary, some of the least desirable overstory trees in order to remove at least 25 percent but no more than 40 percent of the total basal area.
(3) Kill Suppressed Stems. Kill the understory, midstory, and suppressed trees in the overstory without regard to how much basal area was removed.

The “hack and squirt” method of herbicide application was used to kill the targeted trees. Trees down to 0.6” d.b.h. (1-inch class) were treated.

Five study locations were established between 1986 and 1988. Elevations of the study sites ranged from a high of 3,200 feet in Avery (two sites) and Polk counties to 1,100 feet in Caldwell County to a low of 300 feet in Chatham County. Each of the stands had a large proportion of mature oak in the overstory along with yellow-poplar (*L. tulipifera*), hickory (*Carya spp*), black gum (*N. sylvatica*), and red maple (*A. rubrum*). Understory species included dogwood (*C. florida*), sourwood (*O. arboreum*), hemlock (*T. canadensis*), redbud (*C. canadensis*), and red maple. Site indices ranged from 70 to 80 for oak at age 50. The study locations represent the range of typical hardwood stands found in the North Carolina mountains and piedmont on medium-quality upland sites.

Initial average stand basal area levels ranged from 134 to 145 square feet. The average levels of basal area reduction for the two herbicide treatments were very similar. The Oak Shelterwood treatment averaged 33 percent removal with a range of 22 to 38 percent, and the Kill Suppressed Stems treatment averaged 27 percent with a range of 19 to 45 percent.

The study design was randomized block. Treatment plot dimensions were 100 feet by 100 feet. Each location had two replications (blocks) of each treatment; circular 1/10-acre plots were centered inside the treatment plot from which a maximum of 50 oak seedlings were identified, tagged, and measured. The measured seedlings were representative of the oak species and stem sizes present on the plot as advanced reproduction.

The following parameters were recorded for each seedling: species, basal diameter (measured just above the root collar), height, and competitive status (such as being overtopped by other vegetation adjacent to it or whether it was single or multiple stemmed). Later measurements also included any original stem die back and new stem development. Measurements were taken at 1, 2, and 7 years after establishment. Basal diameter was recorded

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only at 1 and 7 years. All surviving stems at 7 years following treatment were included in the survival analyses but immediately overtopped stems and stems with multiple leaders or that had died back were excluded from the diameter and height growth analyses.

Five common oak species were represented in the study. Northern red oak *(Q. rubra)* was most prevalent followed in order by white oak *(Q. alba)*, scarlet oak *(Q. coccinea)*, chestnut oak *(Q. prinus)* and black oak *(Q. velutina)* (fig. 1). Northern red oak and scarlet oak occurred on all study sites. White oak and black oak were present on four of five locations and chestnut oak occurred on three of the five.

Most of the initial advanced oak reproduction was quite small. The largest proportion, 72 percent, was in the 0.1-inch diameter class and only 13 percent was 0.3 inch or larger in diameter (fig. 2).

Initial heights tended to increase with increasing basal diameters, and average beginning heights were similar for each species. Of the five species, all but chestnut oak averaged less than 1 foot tall when the basal diameter was under 0.3 inches (table 1).

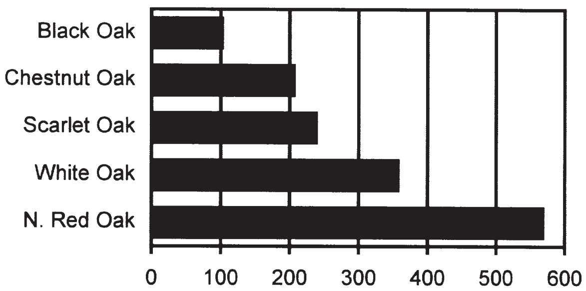

Figure 1—Initial number of seedlings by species for all treatments combined.

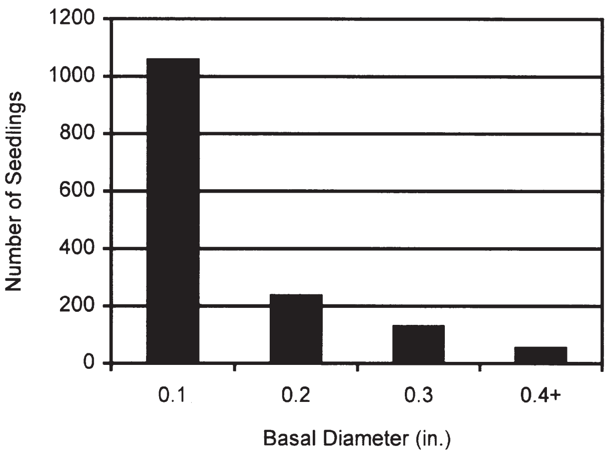

Figure 2—Basal diameter distribution of initial seedlings for all treatments combined.

Table 1—Average initial height by initial basal diameter class and species for all treatments combined

Oak species	Initial basal diameter class 0.1	0.2	0.3	0.4+	Average
	- - - - - -	- - - -Height (*in*)-	- - - -	- - - -	- - - -
Black	5	7	13	28	7
Chestnut	6	13	16	29	9
Northern red	6	10	15	24	8
Scarlet	6	9	11	–	7
White	6	10	16	31	10
Average	6	11	15	28	8

RESULTS AND DISCUSSION

Similar Response by Species

Survival and growth response was similar for the five oak species (table 2). For all treatments combined, survival ranged from 66 to 78 percent. Loftis (1992) found that white oak responded more slowly to release than did black, scarlet, northern red, and chestnut oaks. However, when white oak data were excluded, the basal diameter increases were essentially unchanged for the herbicide treatments. For height growth, white oak was intermediate among the five species. Height growth was slightly more variable among the species than was basal diameter growth.

Survival

Seven-year seedling survival for all species combined increased with increasing initial seedling basal diameter and with an understory treatment to augment sunlight reaching the forest floor (table 3). The control treatment showed a significantly lower average survival than the herbicide treatments. This result is in agreement with the observation of Loftis (1992) that oak seedlings under full shade gradually die in the understory if not exposed to

Table 2—Average survival, basal diameter, and height increases for all treatments combined

Oak species	Survival	Diameter increase	Height increase
	Percent	- - - - - - *Inches*	- - - - - -
Black	75	.08	3.6
Chestnut	78	.06	1.4
Northern red	68	.07	2.3
Scarlet	66	.06	2.7
White	75	.08	3.1

Table 3—Average survival after 7 years by initial diameter class and treatment[a]

Treatment	Initial basal diameter 0.1	0.2	0.3	0.4+	Average
	- - - - - Survival rate (*percent*) - - - - -				
Control	43	69	78	92	53*a*
Oak Shelterwood	73	91	94	100	78*b*
Kill Suppressed Stems	79	94	89	100	83*b*

[a] Average percents followed by a different letter are statistically different according to Duncan's Multiple Range Test (P=0.05).

increased sunlight. No significant difference in survival was detected between the herbicide treatments. The adverse impact of shade was most dramatic on the smallest seedlings, which are typically the most prevalent in upland hardwood stands on medium-quality sites. For the control treatment only about 40 percent of the seedlings in the 0.1-inch diameter class were surviving after 7 years, whereas nearly 70 percent in the 0.2-inch class were surviving.

Changes in Basal Diameter

For all species combined, the herbicide treatments produced a significant increase in basal diameter over the control treatment (table 4). In practical terms, though, the overall advantage of 0.05 inches is only modest at best. In fact the 0.08-inch increase in basal diameter for the treated plots is only one-half that predicted by Loftis (1990b) for the oak shelterwood treatment on medium-quality sites.

Nonetheless, the oak seedlings are developing slowly into larger seedlings. As the seedlings increase in diameter, the proportion in the 0.1-inch class has decreased for all three treatments, while the number of seedlings in each of the other diameter classes has increased. The proportion of increase for the herbicide treatments is larger than the control for each diameter class (fig. 3).

Table 4—Average basal diameter increase by treatment[a]

Treatment	Diameter increase
	- - - - *Inches* - - - - -
Control	0.03*a*
Oak Shelterwood	0.08*b*
Kill Suppressed Stems	0.08*b*

[a] Numbers followed by a different letter are statistically different according to Duncan's Multiple Range Test (P=0.05).

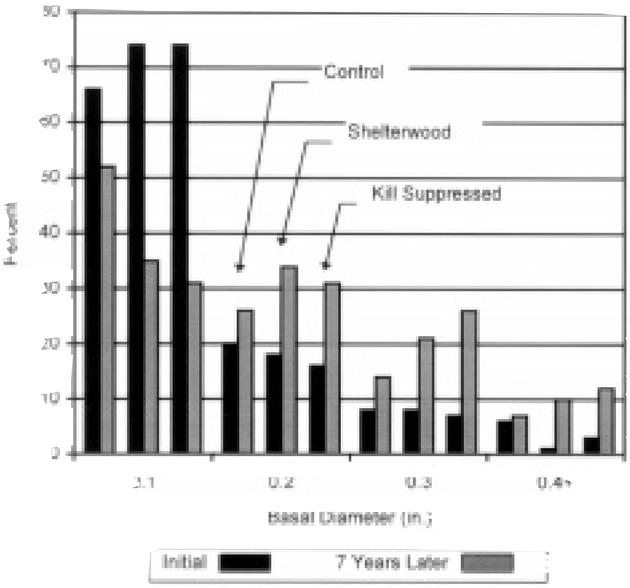

Figure 3—Proportion of seedlings by treatment in each diameter class initially and 7 years after treatment. (For each basal diameter class, Control, Shelterwood, and Kill Suppressed are grouped from left to right).

Changes in Height

For the five species combined there was a significant though small increase in average height growth for the herbicide treatments compared to the control (table 5). The advantage was consistent as the herbicide treatments outperformed the control in each diameter class. However, this net advantage of 2 inches for the herbicide treatments likely is of little practical importance.

The changes in oak seedling height are probably less important than changes in diameter, since the majority of seedlings would be knocked down during logging and would have to resprout from the stump. Nevertheless, height growth does give some indication of how the seedlings are developing since, generally, taller seedlings have larger basal diameters.

Table 5—Average height increase by treatment[a]

Treatment	Average height increase
	- - - *Inches* - - - -
Control	1*a*
Oak Shelterwood	3*b*
Kill All Suppressed Stems	3*b*

[a] Average height increases followed by a different letter are statistically different according to Duncan's Multiple Range Test (P=0.05).

Non-Oak Understory Redevelopment

No measurements were taken to quantify the subsequent development of the non-oak seedlings in the understory that were too small at study establishment to treat (less than 0.5-inches d.b.h.). These were mostly eastern white pine (*P. strobus*), Fraser magnolia (*M. fraseri*), eastern hemlock, dogwood, sourwood, blackgum, red maple, and American holly (*I. opaca*). It is now obvious that these seedlings have developed and grown to the point where they will soon begin shading and suppressing the oak seedlings. Unless the oaks begin to develop faster, it may be necessary to retreat some of the areas to control these competitors.

Another occasional problem observed on treated seedlings outside the measurement plots was the development of honeysuckle (*Lonicera japonica*). Where present, the honeysuckle was stimulated by the increased sunlight and in some cases has developed into a thick mat, entangling and pulling down the small oak seedlings.

SUMMARY AND CONCLUSIONS

Providing sunlight to the small advanced oak reproduction by either of the herbicide treatments significantly improved survival. All five oak species responded in a similar manner. Even white oak, generally acknowledged to be the slowest grower of the upland oaks, responded similarly to the other oaks. The herbicide treatments also provided significant, but small, improvement in basal diameter and height growth. There was no difference in survival or growth response for the two herbicide treatments. Both herbicide treatments removed similar average amounts of stand basal area though the oak shelterwood removal rates were more consistent. Survival of the oak reproduction improved with increasing initial basal diameters for both the herbicide and control treatments, though the herbicide treatments showed consistently higher survival in each initial diameter class.

In practical terms the herbicide treatments were most effective at reducing mortality of the oak seedlings. Though the improved growth response did advance some seedlings into larger diameter classes, the response was only half that predicted by Loftis (1992) for the oak shelterwood. The slow response was especially telling for the small advanced reproduction. After 7 years, very little of the small advanced reproduction, that in the 0.1 and 0.2 basal diameter classes and less than 1 foot in height, has grown enough to be competitive once the overstory is removed. Typically, this small reproduction is the common size found on most upland oak stands on medium-quality sites.

IMPLICATIONS

For the private landowner, these silvicultural techniques may not be practical unless there are very large amounts of advanced oak regeneration already present and there is a willingness to wait a long time for the seedlings to develop. More than 7 to 10 years may be needed for the small advanced reproduction to develop. A complicating factor is that the non-oak competitors are also developing alongside the oak, and additional control measures may be required to keep the oak seedlings from becoming suppressed. Most landowners may not find it feasible to invest in silvicultural treatments more than 10 years in advance of a harvest. Based on these study results, on medium-quality sites, the landowner will either have to wait longer for the oak reproduction to reach an average minimum threshold size, or accept fewer oaks per acre in the next stand.

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GROWTH AND PROTECTION OF SELECTED NORTHERN RED OAK SEEDLINGS PLANTED ON OLD FIELD SITES

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Abstract—High-quality northern red oak (*Quercus rubra* L.) seedlings have been produced at the Tennessee Division of Forestry nursery in Etowah, TN, through the efforts of the University of Tennessee Tree Improvement Programs and the USDA Forest Service. In an effort to begin establishing planting guidelines for these oaks, seedlings from 10 different genetic families were lifted in spring 1995 and visually graded according to size, stem form, bud set, and root characteristics. The selected 1+0 northern red oak seedlings were planted on formerly established grass plots on nine marginal soils at five branch experiment stations in Tennessee. White-tailed deer (*Odocoileus virginianus* Zimmermann) browsed these seedlings heavily, regardless of location. A quantitative measure of browse damage was developed for this study. Due to the confounding effects of damage by deer on the 1995 marginal soils study, another study was initiated in spring 1996 to determine whether graded seedlings could be protected from white-tailed deer when planted on old field sites. Four commercial repellents, Deer-Away Big Game Repellent[R], Hinder Deer and Rabbit Repellent[R], Nortech's Tree Guard[TM], and Pro-Tec Garlic Sticks were applied to field-planted 1+0 northern red oak seedlings from six different genetic families. Six treatments, including Tubex[R] 1.2-meter tree shelters and an untreated control, were replicated three times at separate plots on an area known to have a high deer population, the Chuck Swan Forest and Wildlife Management Area in Union County, TN. Two months after planting, damage by deer was evident in all treatments except for seedlings in tree shelters. Three months after planting, the most heavily browsed seedlings were in the control plots, the Tree Guard plots, and the Pro-Tec Garlic Stick plots. Response to treatments will be evaluated through the second growing season.

INTRODUCTION

Northern red oak (*Quercus rubra* L.) is a highly desirable species for timber production, for providing habitat and mast for wildlife, and for recreational opportunities. However, oak stands, particularly those of red oak, on good to excellent sites are increasingly being replaced by less desirable species after harvesting (Crow 1988, Johnson 1984, Lorimer 1992, McGee and Hooper 1970).

Oak mortality contributes to the decreased stocking level of northern red oak in Tennessee and the Southern Appalachians. In Tennessee, forest resource reports from 1991 show the amount of growing stock that dies has doubled since 1990, and nearly two-thirds of the increase in mortality is occurring in oaks, mostly red oaks (Nebeker and others 1992).

Attempts to artificially regenerate northern red oak are often met with limited success (Loftis 1979). The principal cause is the failure of northern red oak seedlings to exhibit rapid juvenile height growth. This lack of early growth does not allow northern red oak to compete with faster growing vegetation (Beck 1970, Olson and Hooper 1972, Russell 1973). In addition to the problem of slow juvenile growth, seedlings that were commonly planted were smaller and were graded based only on aboveground characteristics. Research has shown that nursery practices of grading bare-root hardwood seedlings based only on shoot characteristics (e.g., height and diameter) have not provided adequate planting stock (Thompson and Schultz 1995). The morphological grading of northern red oak seedlings based on root system characteristics, as well as those of the shoot, could greatly increase growth and survival of planted seedlings (Johnson 1992, Kormanik 1986, Ruehle 1986, Stroempl 1985, Thompson and Schultz 1995). The regeneration problems with northern red oak may be remedied to some extent by producing quality seedlings that can be used to increase the oak component in forest stands and for reforestation purposes.

The objective of this research was to determine whether graded 1+0 northern red oak seedlings from different genetic families would survive and grow on soils unsuitable for cultivated row crops. The potential of many sites for northern red oak possibly could be determined since the soils, selected in a previous study (Fribourg and others 1989), are representative (i.e., droughty, eroded, poorly drained, etc.) of marginal soils found throughout the State. Should families show a range of responses, genotypes could be isolated that will perform best on various soils.

Following extensive damage to oak seedlings by white-tailed deer (*Odocoileus virginianus* Zimmermann) at all planting locations, an attempt was made to quantitatively record damage done by deer. A second study was then established in spring 1996. This study was designed to determine whether graded 1+0 northern red oak seedlings planted on old field sites could be protected from deer and, if so, whether seedlings from different genetic families would show varying responses to different treatments.

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METHODS

1995 Marginal Soils Study

Acorns were collected from the USDA Forest Service northern red oak seedling orchard in Carter County, TN. Seedlots were collected from nine mother trees (pollen parent seed source unknown). Acorns were planted at the Tennessee State nursery in Etowah in February 1994 at a density of 280 acorns per square meter. Seedlings were grown without undercutting or top-pruning. They were lifted in the fall of 1994 and overwintered in cold storage.

Before outplanting in spring 1995, seedling stock was graded by number of first-order lateral roots (FOLR), stem form, and bud set. Approximately two-thirds of the seedlings were culled at the nursery. Larger seedlings having a minimum of six FOLR were selected for planting. Tap roots were pruned when dormant to 30.5 centimeters, and FOLR were pruned to 15.2 centimeters.

Seedlings were then outplanted in an incomplete block design on formerly established grass plots on nine marginal soils at five University of Tennessee branch experiment stations (table 1). Since the number of families per replication and soil series was determined by available space, all nine families were not planted in each replication or at every location. Families were assigned to the five locations favoring nearby seed sources over distant ones. Seedlings were planted in five rows of eight seedlings per family on a 1.8- by 2.4-meter spacing. Because of seedling size, augers were used to ensure holes were big enough to accommodate the large root systems. Height and root collar diameter (RCD) measurements were taken after outplanting. Measurements of height were made to the nearest 0.1 centimeter, and diameter was measured to the nearest 0.01 millimeter. Glyphosate herbicide was sprayed around each seedling 1 month after planting. Data for survival and field measurements were analyzed using the General Linear Model analysis of variance procedure of the Statistical Analysis System (SAS Institute, 1985) and comparisons were made using Tukey's Studentized (HSD) Range test.

Table 1—Northern red oak outplanting locations by family and experiment station for 1995 marginal soils study

Experiment station and soil series	Families	Replications
Ames Plantation	2,3,4,7,9	
Lexington (APL)		3
Alamo (APA)		3
Memphis (APM)		3
Ruston (APR)		2
Cumberland Forest	1,4,5,6,10	
Wolftever (CFW)		2
Philo (CFP)		2
Oak Ridge	1,2,4,7,10	
Armuchee (ORA)		4
Tullahoma	2,4,7,9,10	
Dickson (TFD)		3
West Tennessee	2,3,4,7,9	
Collins (WTC)		3

In a study done by Meyers and others (1989) with planted northern red oak, browse damage was a factor, but no quantitative measurement of the effect of browsing on height growth or survival was made. For this study, a deer damage rating system was developed to assess quantitatively the severity of browse damage, and possibly to determine whether there were location or family differences. For maximum efficiency, no further measurements were taken. Instead, seedlings were assigned a subjective rating of 0 to 4, based on an ocular estimate of the deer browse damage. Seedlings were rated in mid-July 1995 and again in summer 1996. Seedlings that were unbrowsed received a rating of 4, seedlings that had 25 percent or less damage were rated 3 (lightly browsed), seedlings that received damage from 26 to 75 percent (heavily browsed), received a rating of 2, and seedlings damaged from 76 to 99 percent (severely browsed) were rated 1. Seedlings rated 0 (completely defoliated) appeared to be dead at the time of assessment, but may be capable of resprouting.

1996 Deer Repellent Study

Northern red oak seedlings for the 1996 study were sown, planted, and graded at the State nursery under the same protocol as was presented for the marginal soils study above. Seedlings were lifted in fall 1995 and overwintered in cold storage. They were planted in spring 1996 on 18 old field plots located at the Chuck Swan Forest and Wildlife Management Area in Union County, TN. This area is known to have a large deer population, and incidence of browse damage was expected. Four commercial repellents, Deer-Away Big Game Repellent®, Hinder Deer and Rabbit Repellent®, Nortech's Tree Guard™, and Pro-Tec Garlic Sticks were applied to field-planted 1+0 northern red oak seedlings. Tree Guard has not been approved for use in Tennessee, but permission was obtained for its use for research purposes. Two other treatments were Tubex ® 1.2-meter tree shelters and an untreated control. All six treatments were replicated three times on seedlings from six genetic families, with two families in each replication.

Seedlings were planted in late March on a 3- by 3-meter spacing in two rows of eight seedlings each. Initial height and RCD were measured, and deer repellent treatments were applied at that time. Glyphosate herbicide was sprayed around each seedling 1 month after planting. Seedlings treated with spray applications of Hinder, Deer-Away, and Tree Guard were retreated 50 days after planting when new growth averaged 10 centimeters. Missing garlic sticks were also replaced. Seedlings were monitored closely for signs of browse damage the first 2 months after planting, and browse damage ratings (as described for the 1995 study) were recorded for each seedling at the time of retreatment. Browse damage ratings were then recorded three more times throughout May and June. Data for survival and field measurements of the seedlings were analyzed using the same procedure as was presented for the 1995 study.

RESULTS

1995 Marginal Soils Study

Seedling survival—Overall survival rates declined from 94 percent in the first year to 58 percent at the end of the second growing season (table 2). Survival in the second growing season was good and ranged from 85 to 90 percent at three Ames Plantation locations on the Alamo (APA), Memphis (APM), and the Ruston (APR) soil series sites.

There were no significant differences in first-year survival by browse damage level among browsed seedlings rated 3, 2, or 1 (99, 99, and 96 percent). Survival of 72 percent for seedlings rated 0 (totally defoliated) was less than survival at all other damage level ratings. Seedlings that had been completely defoliated by deer had the highest mortality. Variation in survival that could be attributed to browse damage was significant in both growing seasons at the same p level ($p = 0.0001$). Second-year survival was 100 percent for seedlings given a rating of 3 (lightly browsed). Of the seedlings rated 0 in 1995, 96 percent did not change rank when rated in 1996 and mean survival dropped to 3 percent.

Seedling growth—Seedlings planted at the Ames Plantation Memphis series location (APM), which served as the control and is not a marginal soil, outperformed seedlings at all other locations (fig. 1). Significant differences ($p < 0.05$) in height growth occurred between seedling groups rated 3 and 2 in both the first and second growing seasons (table 3). There were no differences between seedling groups rated either 0 or 2 in the first year. Seedlings with the smallest increase in height, those

Table 2—Mean survival of 1+0 northern red oak seedlings after outplanting on marginal soils

Experiment station and soil series	Year[a] 1995	1996
	- - - - - -*Percent*- - - - -	
Ames Plantation		
Lexington (APL)	92ab	78bc
Alamo (APA)	97a	90a
Memphis (APM)	98a	88ab
Ruston (APR)	91ab	85ab
Cumberland Forest		
Wolftever (CFW)	95a	29e
Philo (CFP)	98a	62d
Oak Ridge		
Armuchee (ORA)	92ab	28e
Tullahoma		
Dickson (TFD)	86b	68cd
West Tennessee		
Collins (WTC)	97a	9f
Mean	94	58

[a] Means within a column with the same letter are not significantly different (p<0.05) using Tukey's Studentized Range (HSD) Test.

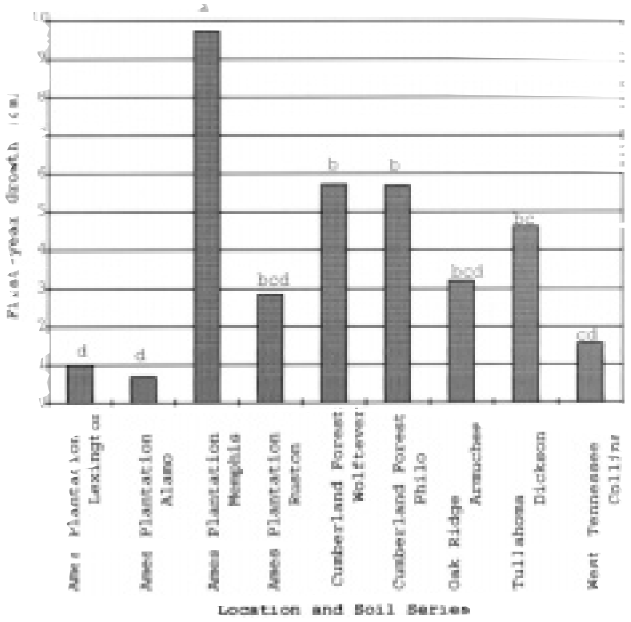

Figure 1—First-year mean height growth of selected 1+0 northern red oak planted on marginal soils in 1995. Bars with the same letter are not significantly different ($p < 0.05$) using Tukey's Studentized Range (HSD) Test.

Table 3—Annual and cumulative incremental height, and diameter growth of 1+0 northern red oak planted on marginal soils, by four deer damage levels

Damage level	First year[a]	Second year	Cumulative (2 yrs)
	- - - - - - - - - - - *Height* - - - - - - - - - - -		
0=Defoliated	2.3bc	-12.6c	-9.1c
1=Severe	0.9c	-17.4c	-15.3c
2=Heavy	3.0b	2.2b	7.3b
3=Light	7.4a	19.5a	26.3a
Mean	3.8	0.4	5.1
MSD[b]	1.9	12.0	12.4
	- - - - - - - - - - -*Diameter*- - - - - - - - - -		
Defoliated	0.52a	0.06c	0.31b
Severe	0.50a	-0.19c	0.58b
Heavy	0.48a	1.43b	2.10b
Light	1.09a	3.47a	4.66a
Mean	0.68	1.39	2.13
MSD	0.61	1.31	2.46

[a] Means within a column with the same letter are not significantly different (p<0.05) using Tukey's Studentized Range (HSD) Test.
[b] Minimum Significant Difference (p<0.05).

rated 0 and 1 (completely defoliated and severely browsed), were not different in 1995 and 1996. These results are similar to those found by Auchmoody and Walters (1992), who demonstrated that the height of planted seedlings was affected more by browsing pressure than by light if unprotected from deer.

There were no differences in diameter growth among any of the damage ratings the first year. In the second year, seedlings rated 1 and 0 were not different from each other. Seedlings rated 2 and 3 showed the largest increase in diameter (1.4 and 3.5 millimeters, respectively) and were different from each other and from seedlings rated 0 or 1.

1996 Deer Repellent Study

Seedling survival—Just as in the 1995 study, first-year survival was high. Family, treatment, and damage rating variables were not different ($p < 0.05$) in survival the first year. Survival across all treatments was 98 percent. Survival of seedlings with a damage level of 1 (85 percent) was different from that of seedlings rated 2, 3, or 4 (99, 100, and 98 percent). There were no seedlings rated 0 in this study.

Seedling growth—Differences in height growth attributed to treatment were apparent ($p < 0.05$). Protection provided by Tree Guard was limited. Garlic Sticks and Deer-Away seemed to be most effective early on. When browse damage percentages were compared among the six treatments (fig. 2), tree shelters clearly surpassed all other deer repellent treatments. Seedlings in tree shelters had substantial increases in height the first year, and were different from all other treatments. The increased height growth of seedlings in shelters was similar to the results of Lantagne and others (1990) with northern red oak planted in a Michigan clearcut. Height growth ranged from 0.6 centimeters in the control to 52.8 centimeters for seedlings in tree shelters (table 4). Level of browse damage was also significant for height growth ($p = 0.0425$). Seedlings rated 4 (unbrowsed) had a mean height growth of 33.2 centimeters

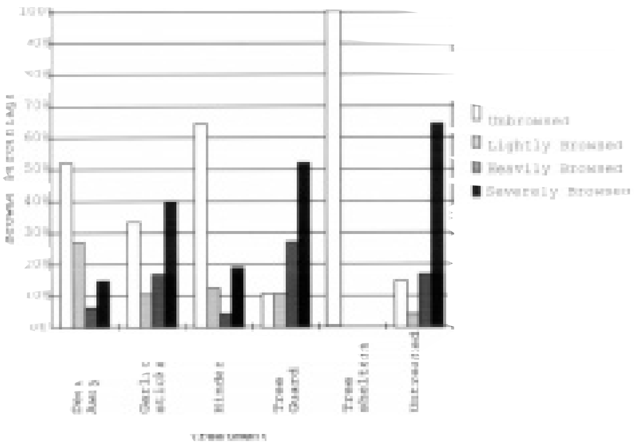

Figure 2—Comparison of four levels of browse damage among six treatments applied to selected 1+0 northern red oak planted at Chuck Swan Forest and Wildlife Management Area.

and were significantly different from seedlings rated 3, 2, or 1. However, this rapid growth for the unbrowsed seedlings can be attributed to the increased growth of seedlings in the tree shelter treatment. Seedlings rated 3 and 2 were not different from each other (12.9 and 5.4 centimeters), but were different from seedlings rated 4 or 1. Seedlings that received a rating of 1 (completely defoliated) did not increase in height and were, in fact, shorter than when they were planted. However, only 6 percent of the seedlings fell into this category.

Diameter growth across all treatments was 1.0 millimeter. The largest increase in diameter was recorded in the Deer-Away treatment (1.4), and the smallest was in the Garlic Stick plots (0.6). Seedlings in tree shelters had the second largest increase in diameter, and apparently diameter growth occurred even when seedlings had large increases in height. Larger select seedlings planted in shelters are not only protected from browse, they may be less spindly and have the possible advantage of removal from the shelter in two growing seasons.

DISCUSSION

Seedlings at a few locations grew well in 1995, but overall performance was discouraging. Loftis (1979) has reported that height growth of less than 30.5 centimeters per year is considered poor, and even at the location where best results were obtained, mean growth in the 1995 study was less than 10 centimeters in the first year. Growth rates were unacceptably slow, damage by deer was widespread, and mortality was high in the second year.

Extensive damage to seedlings by deer was recorded in both the 1995 and 1996 studies. When browse damage became apparent in 1995, Pro-Tec Garlic Sticks were applied to seedlings at every location in early June, except for those planted at Tullahoma. Browse damage to the seedlings at this location became apparent approximately 1 month later. Garlic Sticks were applied at that time. Since repellents were applied to seedlings at Tullahoma after browse damage had already occurred, protection may have been minimal. Gillingham and Bunnell (1989) conducted research on the feeding habits of black-tailed deer (*Odocoileus hemionus columbianus* Richardson) and found that memory may play an important role in the foraging activities of deer. The results of the marginal soils study would suggest that some form of protection from deer is needed at planting time, and should be applied before feeding habits are established.

Presently, outside of Pennsylvania, published evidence on the effects of deer browsing on oak has been very limited. Lorimer (1992) stated that researchers have found that establishing hardwood plantations is often like “setting the table for deer,” and more evidence is needed on the effects of moderate deer browsing on growth rates of oak. Seedlings planted for the deer repellent study in 1996 were protected initially, and several repellent treatments seemed to deter further browsing. From planting time until budbreak, no browse damage was recorded, and even in the untreated plots deer did not begin to browse the

Table 4—Height and diameter growth of 1+0 northern red oak planted at Chuck Swan Forest and Wildlife Management Area by treatment and deer damage level

	Damage level				
Treatment	Mean[a]	Severe	Heavy	Light	Unbrowsed
	Height (cm)				
Deer Away	9.6bc	-25.5	8.7	7.6	15.5
Garlic Sticks	5.6bc	-7.5	6.3	10.8	5.5
Hinder	13.1b	—	8.2	16.9	12.8
Tree Guard	5.8bc	0.00	5.4	10.8	—
Tree Shelters	52.8a	—	—	56.0	52.7
Untreated	0.6c	-6.7	2.5	—	—
Mean[b]	15.4	-8.3c	5.4b	12.9b	33.2a
	Diameter (mm)				
Deer Away	1.44a	0.06	1.32	1.57	1.57
Garlic Sticks	0.57c	0.32	0.54	0.64	1.50
Hinder	1.09ab	—	0.79	1.09	1.18
Tree Guard	0.78bc	0.10	0.69	1.70	—
Tree Shelters	1.14ab	—	—	1.00	1.15
Untreated	0.94abc	0.87	0.96	—	—
Mean[b]	1.01	0.55b	0.80ab	1.28a	1.25a

[a] Means within a column with the same letter are not significantly different ($p<0.05$) using Tukey's Studentized Range (HSD) Test.
[b] Means with the same letter within rows are not significantly different.

seedlings until approximately 6 weeks after planting. Seedlings that were treated with some form of deer repellent outperformed unprotected ones. No seedlings were completely defoliated in the 1996 study, and there may be two possible reasons for this outcome: deer did not become accustomed to browsing the seedlings because protection was applied at planting time or, because it is a wildlife management area, plenty of other food sources were available.

CONCLUSIONS

Results from both studies indicate that browse damage ratings assigned to northern red oak seedlings are helpful in identifying which ones are expected to respond and recover, and which seedlings are more likely to die. In areas where browse pressure is a concern, protection from deer in the first few years after planting is crucial to the early growth and development of northern red oak seedlings. The increased growth rate and excellent early performance of these select seedlings in tree shelters deserves further study.

ACKNOWLEDGMENT

We would like to thank the Ames Foundation near Grand Junction, TN, for partial support of this investigation. It is owned and operated by the trustees of the Hobart Ames Foundation under the terms of the will of the late Julia C. Ames. Appreciation is extended also to the Tennessee Division of Forestry, and the Tennessee Wildlife Resources Agency for their assistance in the research. Special thanks to Allan Houston, Richard Evans, Gordon Percell, Tim Seay, and Steve Roark.

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NATURAL ESTABLISHMENT OF WOODY SPECIES ON ABANDONED AGRICULTURAL FIELDS IN THE LOWER MISSISSIPPI VALLEY: FIRST- AND SECOND-YEAR RESULTS

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Abstract—The natural establishment of woody seedlings on abandoned agricultural fields was investigated at sites in Louisiana and Mississippi. Series of disked and undisked plots originating at forest edges and oriented in cardinal directions were established on fields at each site. During the first 2 years, seedling recruitment was dominated by sweetgum, sugarberry, and elms at both sites. Seedling establishment was strongly affected by direction from mature forest and disking, and to a slightly lesser degree by distance from mature forest. Slightly under half of the variation in seedling numbers per plot was explained by the effects of direction, distance, and disking, indicating that other factors also may play an important role in seedling recruitment.

INTRODUCTION

A typical restoration project in the Lower Mississippi Valley region involves the establishment of two to three overstory tree species, usually oaks (esp. *Quercus nuttallii*, *Q. phellos*, *Q. nigra*, and *Q. pagoda*), either by planting 1-year-old bare-root seedlings or by direct seeding acorns. The techniques used to reforest former agricultural lands have been described in more detail elsewhere (Allen and Kennedy 1989).

It is generally assumed that establishment of other woody species will occur through natural dispersal and that a mixed-species forest will develop over time. There is, however, evidence that a mixed-species forest does not always develop, at least during the first 25 to 50 years. For example, Haynes and Moore (1988) noted that while some reforestation sites in the Lower Mississippi Valley appeared to have a desirable degree of species diversity, others did not. Also, although Allen (1990) found that average stocking of invader species on 10 reforestation sites was fairly high overall, most of the established trees were within 60 meters of mature forest (Allen, in press). Among the factors suggested by Haynes and Moore (1988) as possible causes of the reduced establishment of invading woody species was the lack of available seed sources, which may be largely a factor of distance and direction to mature forest or trees.

Land managers responsible for restoration could benefit from information on patterns of natural invasion of woody species. On sites where natural invasion is expected to be slow, planting species other than oaks may prove beneficial. On sites where natural invasion is expected to be more rapid, it might be cost effective to plant only oaks and rely on natural regeneration to provide the desired species diversity. The problem—and the justification for this study—is that it is not yet clear which sites (or portions of large sites) will have adequate natural invasion.

METHODS

This study is being conducted on two sites: (1) a former farm located in Sharkey County, MS, (the Sharkey Site) and (2) Lake Ophelia National Wildlife Refuge (NWR), near Marksville, LA. Most of the Sharkey Site was transferred to the U.S. Fish and Wildlife Service from the Farmers Home Administration in 1993. A small portion on the southern end of tract was transferred to the USDA Forest Service (Delta National Forest).

The Sharkey Site is approximately 820 hectares and is located about 8 kilometers east of Anguilla, MS. Most of the site has been cleared since the early 1960's. A recent on-site inspection by a Natural Resource Conservation Service employee found most to be Sharkey clays. On the highest sites, there are small areas of Dundee silt loams and Forestdale silty clay loams.

Lake Ophelia NWR is located on the Red River floodplain in east central Louisiana (Avoyelles Parish). The 5,990-hectare refuge is characterized by meandering channels, shallow sloughs, oxbow lakes, cypress-tupelo swamps, and bottomland hardwoods. The overall configuration of the area is a combination of ridges and swales with only slight changes in elevation. Soils in the area are roughly 50 percent Tensas silty clays and 40 percent Sharkey clays. Much of the refuge is currently open land that is still farmed, or land that was cleared and is now in various stages of reverting back to forest. The refuge is prone to both backwater flooding and shallow flooding from local precipitation (U.S. Fish and Wildlife Service 1988).

In the fall of 1994, a series of transects was laid out at each site in cardinal directions, originating at the edges of mature forests and proceeding into recently abandoned agricultural fields. Each transect consists of one disked and one undisked section, each 30 meters by 150 meters. Within each section a series of eight 0.01-hectare (10 by 10 meters) plots were established at 20-meter intervals; plot mid-points range from 5 meters to 145 meters from the forest edge. Where possible, three transects were established in each of the four cardinal directions at each study site. Limitations on the availability of suitable sites resulted in the following

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exceptions: (1) only two west-facing transects could be established at the Sharkey Site, and (2) only two north-facing and no east-facing transects could be established at Lake Ophelia NWR. A total of 19 transects and 304 plots was established.

All the transects at Lake Ophelia and the north-facing transects at the Sharkey Site were on fields farmed less than 1 year prior to their establishment. These fields were essentially devoid of competing vegetation prior to the 1995 growing season. The remainder of the transects on the Sharkey Site were established in fields that had been out of production for 1 or 2 growing seasons. The transects on these fields were bush-hogged prior to plot establishment.

Woody vegetation established on the plots was measured in the late fall of 1995 and 1996. A complete census of woody stems was made on each plot. Two 1-square meter subplots were located within each main plot to characterize herbaceous vegetation. Ocular estimates of percent cover were made for total cover and cover for each of the most common herbaceous species.

A four-way analysis of variance was performed on the 1996 data to test for the effects of direction, distance, disking, and site on the number of seedlings established per plot. All four factors were treated as fixed effects. Because the mean number of seedlings per plot was small (<10 in both years) and many plots had no seedlings, a square root transformation (of the number of seedlings per plot + ½) was employed (Steel and Torrie 1980). Statistical analysis was performed using the GLM procedure of the Statistical Analysis System (SAS, Release 6.11). Only descriptive statistics are presented for herbaceous vegetation.

RESULTS AND DISCUSSION

Herbaceous Vegetation

At Lake Ophelia NWR, where all fields were in their first year after abandonment in 1995, annuals (*e.g.*, *Sida rhombifolia*) were an important component of the herbaceous vegetation. The importance of annuals declined in 1996 at Lake Ophelia NWR, and perennials such as *Aster* spp. and *Solidago* spp. grew in overall importance (table 1). At the Sharkey Site, where most fields had been abandoned for a longer period, perennials were dominant in both years.

Broad similarities between the two study sites were evident, but there were also some potentially important differences. Johnson grass (*Sorghum halepense*), for example, was an important component of the vegetation at the Sharkey Site, especially in 1995, but was relatively uncommon at Lake Ophelia NWR (table 1).

Most herbaceous species were found on both disked and undisked plots, but their relative importance often varied. Disking eliminated raised planting rows, which, because of their slightly higher elevation, offered drier microsites than adjacent furrows. Disking therefore favored species more tolerant of soil saturation (*e.g.*, *Iva annua*), while drier-site species (e.g., *Andropogon glomeratus*) were more common on undisked plots (table 1).

Table 1—Importance value (IV200; relative frequency + relative cover) for selected herbaceous species by study site, year, and disking

	Lake Ophelia NWR				Sharkey Site			
	1995		1996		1995		1996	
Species	Disk	No Disk	Disk	No Disk	Disk	No Disk	Disk	No Disk
Aster spp.	25.3	31.6	65.7	56.4	45.4	38.5	61.3	53.9
Andropogon glomeratus	2.2	3.7	11.8	29.8	4.5	10.8	2.7	7.5
Desmanthus illinoensis	0.0	0.0	0.0	0.0	7.8	6.5	17.0	16.1
Iva annua	25.1	22.0	58.6	31.9	25.4	22.7	27.2	18.6
Sida rhombifolia	24.0	25.9	0.0	0.0	1.4	1.4	0.0	0.0
Solidago spp.	10.4	8.7	20.1	28.1	24.6	29.9	33.8	44.7
Sorghum halepense	5.7	4.1	6.4	3.7	50.1	53.7	24.1	26.9
Xanthium struimarium	27.3	16.7	1.5	0.4	0.0	0.0	0.0	0.0
Other species	80.0	87.3	35.9	49.7	40.8	36.5	33.9	32.3

Overall Seedling Abundance

A total of 1,071 woody seedlings were censused on the two sites in 1995 for an overall average of 351 seedlings per hectare. Most of the seedlings (727) were classified as sprouts from seedlings already established on the Sharkey Site fields that had been abandoned for more than one growing season. Fifteen woody species or species groups were found, of which sweetgum (*Liquidambar styraciflua*) and elms (*Ulmus* spp.) were the most common (table 2), followed by sugarberry (*Celtis laevigata*) and persimmon (*Diospyros virginiana*). Oaks (*Quercus* spp.) and other heavy-seeded species were relatively uncommon.

By the end of the 1996 growing season, the mean number of seedlings increased to 605 per hectare. Most species increased in abundance in the second year; the few with large declines were relatively rare species (table 2).

The general pattern of seedling abundance and species composition was similar at the two study sites. At the end of the 1996 growing season, there was no significant difference in overall seedling abundance between the two sites (table 3). The same three species or species groups (sugarberry, sweetgum, and elms) were the most common at both sites, although their relative abundance differed. Elms were the most common seedlings on the Sharkey Site and sugarberry was by far the most common on Lake Ophelia (table 2). In addition to the large number of sugarberry seedlings at Lake Ophelia NWR, other notable differences between the two sites include the total absence of boxelder (*Acer negundo*) and the smaller number of persimmon at Lake Ophelia NWR.

Effects of Direction from Mature Forest

The orientation of transects with respect to adjacent mature forest had a significant effect on seedling establishment (table 3). Significantly more seedlings were found per plot on the east- and, to a lesser degree, north-facing transects than along those facing south and west (fig. 1). This pattern is not unexpected, given the prevailing wind patterns in the region, which are affected by both the west-to-east jet stream and frequent fronts moving northeast from the Gulf of Mexico.

Effects of Distance from Mature Forest

The effect of distance from the forest edge was not significant at the 0.05 level (table 3; fig. 2a). A more rapid decline in the number of seedlings with distance from the forest edge has been found in other studies (Harper 1977; Hughes and Fahey 1988; Allen, in press). We suspect that the more typical pattern is obscured in our case by the relatively high number of seedlings that may have been

Table 2—Mean number of woody species seedlings (excluding vines) found per hectare by study site and year

Species	Sharkey Site 1995	Sharkey Site 1996	Lake Ophelia 1995	Lake Ophelia 1996	Total 1995	Total 1996
Acer negundo	52.4	48.2	0.0	0.0	30.1	27.9
Acer rubrum	12.6	21.0	5.4	15.6	9.6	18.8
Amorpha fruticosa	0.0	0.5	0.0	0.0	0.0	0.3
Celtis laevigata	55.6	95.3	48.4	248.5	52.6	159.6
Cephalanthus occidentalis	0.0	17.5	3.2	3.2	1.2	11.6
Cornus spp.	0.0	0.0	0.0	4.7	0.0	2.0
Crataegus spp.	12.6	14.8	6.2	33.6	9.9	22.7
Diospyros virginiana	31.1	65.2	25.7	23.5	28.9	47.7
Forestiera acuminata	.0	0.0	2.2	0.0	1.0	0.0
Fraxinus spp.	14.8	31.1	0.7	17.3	8.9	25.2
Gleditisia spp.	1.2	1.7	0.0	0.0	0.7	1.0
Ilex decidua	14.1	19.8	0.0	0.0	8.1	11.6
Liquidambar styraciflua	138.6	118.6	44.5	110.2	98.8	115.0
Planera aquatica	0.0	0.0	0.7	0.0	0.3	0.0
Platanus occidentalis	0.0	0.0	1.5	0.7	0.7	0.3
Quercus spp.	8.4	6.9	14.8	19.5	11.1	12.1
Salix nigra	0.0	1.7	0.0	0.7	0.0	1.2
Ulmus spp.	134.6	174.4	28.2	112.4	89.7	148.2
Total per acre	476.0	616.7	181.5	589.9	351.6	605.2

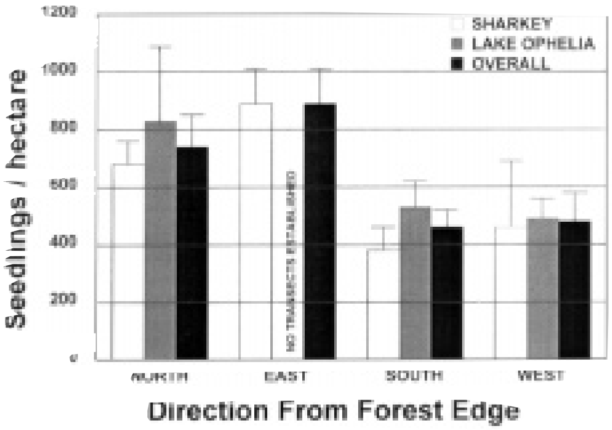

Figure 1—Second-year seedling establishment (mean ± 1 SE) in relation to direction of transect orientation from adjacent forest.

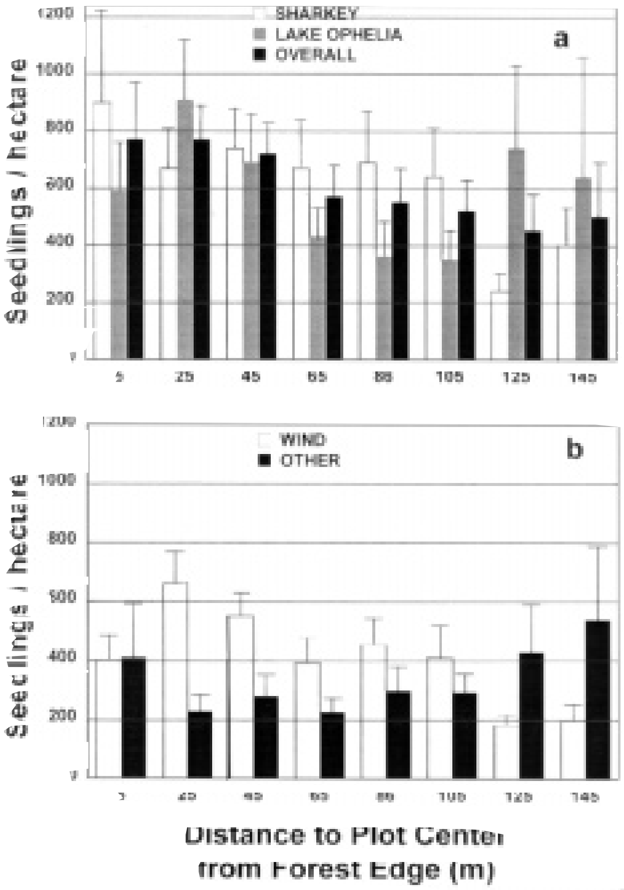

Figure 2—Second-year seedling establishment (mean ± 1 SE) as affected by (a) distance from forest edge and (b) distance and means of seed dispersal.

dispersed by water or animals. Species believed to be dispersed primarily by means other than wind are more common than wind-dispersed seedlings at the farthest distances evaluated (fig. 2b). The high standard errors for the other than wind-dispersed seedlings at 125 meters and 145 meters from the forest edge are caused by high numbers of seedlings found in several plots where localized clumps of sugarberry (possibly due to wracking) occurred, mainly at Lake Ophelia NWR.

Effects of Disking

Disking had a very pronounced effect on seedling establishment (table 3). More than twice as many seedlings

Table 3—Analysis of variance table for the effects of direction from mature forest, distance from mature forest, disking, and site on the mean number of seedlings per plot

Source	DF	Type III Sum of Squares	F Value	p
Direction (DIR)	3	33.473	8.08	0.0001
Distance (DIS)	7	19.023	1.97	0.0613
DIR*DIS	21	28.523	0.98	0.4854
Disking (DISK)	1	57.044	41.31	0.0001
DIR*DISK	3	9.461	2.28	0.0803
DIS*DISK	7	2.950	0.31	0.9509
DIR*DIS*DISK	21	33.483	1.15	0.2959
Site	1	2.757	2.00	0.1593
DIR*SITE	2	5.004	1.81	0.1661
DIS*SITE	7	15.683	1.62	0.1311
DIS*DIS*SITE	14	27.112	1.40	0.1549
DISK*SITE	1	12.183	8.82	0.0034
DIR*DISK*SITE	2	4.707	1.70	0.1847
DIS*DISK*SITE	7	7.096	0.73	0.6433
DIR*DIS*DISK*SITE	14	14.514	0.75	0.7210

were found on undisked plots than on disked plots (fig. 3). The large soil clods and possibly a soil surface more prone to drying and high temperatures may be major factors responsible for lower seedling establishment on disked plots. The higher microsites found on the undisked plots were probably also a very significant factor. The tendency for seedlings to be found on the raised planting rows, rather than in the adjacent furrows, was especially evident at Lake Ophelia NWR. Although there were differences in herbaceous vegetation between disked and undisked plots, it appears that the effect of disking on availability of suitable microsites was more important than vegetation differences in its effect on woody species establishment.

The only significant interaction found in the 1996 data was for disking by site (table 3). We attribute this to the wetter conditions prevailing at Lake Ophelia NWR, which probably made small differences in microsite even more critical. The greater response of seedling establishment to disking for Lake Ophelia NWR is evident in figure 3.

Other Factors Affecting Seedling Establishment

The four-way ANOVA model had an R^2 of 0.49, indicating that slightly over half of the variation observed in seedling establishment was due to factors other than those

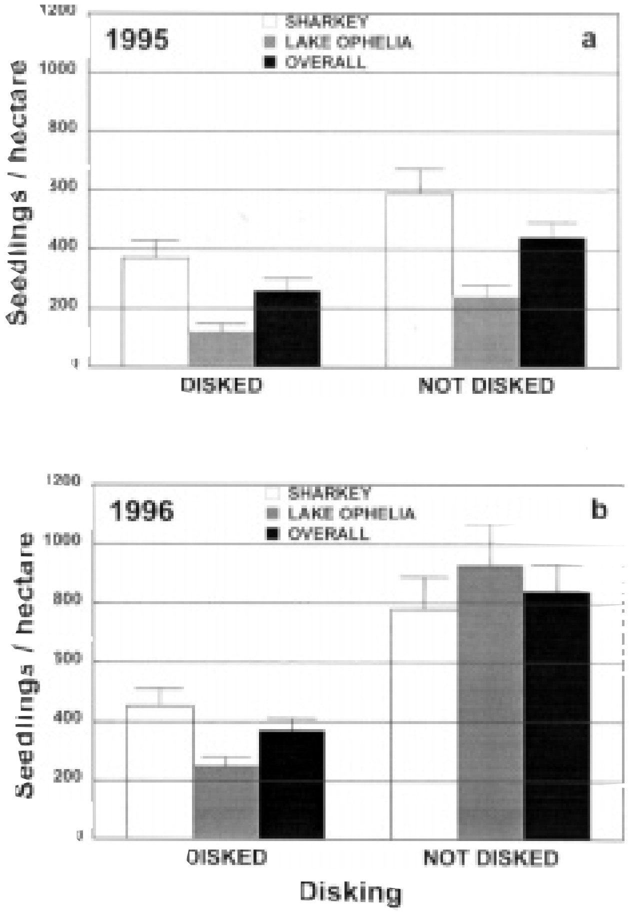

Figure 3—Seedling establishment (mean $\pm$ 1 SE) as affected by disking in (a) 1995 and (b) 1996.

evaluated. Other factors that may be important—besides the inevitable measurement error associated with finding seedlings in dense herbaceous vegetation—include differences (1) in time since abandonment, (2) in species composition of the adjacent forests, and (3) in microsite characteristics within and amongst fields. Another factor that may be important is the pattern of fields versus forest in the vicinity of each transect, which probably influences localized wind speed and turbulence, as well as perhaps having an impact on the total number of seed available for dispersal at any given site.

CONCLUSIONS

Fields at both study sites are going through a pattern of old-field succession that appears to be typical for the region, and which may eventually result in bottomland forest stands of moderately high species diversity. It is clear, however, that the general course of old-field succession is being affected by factors such as the distance and direction of the field from mature forest, and by whether or not the field has been disked.

There are several implications of this research for resource managers involved in bottomland hardwood forest restoration. First, the overall emphasis on planting heavy-seeded species with limited dispersal capabilities, such as oaks and hickories (*Carya* spp.), appears to be fairly well-justified. It is likely that species diversity within restored stands could be increased substantially, however, with supplemental plantings of other species. Supplemental plantings may be most effective in fields oriented to the west and south of mature forest and at distances of greater than about 60 to100 meters from forest edges. Sweetgum, elms, and sugarberry generally establish in sufficient numbers, but almost all other species found in bottomland systems might be good candidates for supplemental plantings. Disking appears to be a mixed blessing. Disking usually enhances survival and growth of planted seed or seedlings (Haynes and others 1995), but, especially on wetter sites, it may temporarily reduce the natural establishment of other seedlings.

ACKNOWLEDGMENT

The authors would like to thank the staffs of the Yazoo NWR Complex, Lake Ophelia NWR, and the Delta National Forest for providing access to the two study sites and carrying out the site preparation required for installation of the study. We would also like to thank Robert LaFleur, Wayne Norling, Monica Moore, Matt Sevier, Chris Wells, and Parker Day for assistance in plot establishment and data collection. Drs. Darren Johnson and James Baldwin provided statistical advice.

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RIVERFRONT HARDWOOD REGENERATION 1 YEAR FOLLOWING COMPLETE AND PARTIAL OVERSTORY HARVESTING

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Abstract—Emphasis on bottomland hardwood regeneration research has focused on the oaks (*Quercus* spp.). Information is needed on the regeneration dynamics of other bottomland hardwood species including those associated with the riverfront hardwood type. Therefore, a study was established in 1995 to follow the long-term establishment and development of bottomland hardwood regeneration. Two harvesting methods, clearcutting and selection cutting, along with an unharvested control were established in the winter of 1995/1996. First-year results showed that harvesting and growing season flooding had an impact on first-year survival and growth. One species, sugarberry (*Celtis laevigata*), responded well to the harvesting treatments. All other species responded less favorably.

INTRODUCTION

In the past 15 to 20 years research in bottomland hardwood regeneration has focused on oak (*Quercus* spp.) species (Clark 1993, Hodges and Janzen 1987). Evidence for this includes the number of bottomland hardwood papers presented at recent biennial southern silvicultural research conferences (Brissette 1993, Edwards 1995) and the number of oak-specific symposiums (Loftis and McGee 1993). While oaks constitute an important component of southern bottomland hardwood forests, other commercially important tree species exist (Putnam and others 1960). These species include those of the riverfront hardwood association, namely cottonwood (*Populus deltoides*), green ash (*Fraxinus pennsylvanica*), sweet pecan (*Carya illinoensis*), and sugarberry (*Celtis laevigata*). Given the importance of an increasing understanding of bottomland hardwood ecosystem structure and function, information is needed on the regeneration dynamics of nonoak species. Therefore, a study was initiated to: (1) determine the response of advanced riverfront hardwood regeneration to two levels of harvesting, (2) determine the composition and development of new riverfront hardwood regeneration following two levels of harvesting, and (3) test a regeneration evaluation model recently developed for coastal plain bottomland hardwood types (oak types).

METHODS

The study site is located on Pittman Island in Issaquena County, MS, adjacent to the Mississippi River and approximately 3 miles south of the Arkansas border. This island is located within the unprotected portion of the Mississippi Alluvial Plain (inside the levees); therefore, it is subjected to periodic flooding. Topography is ridge/swale with differences in elevation of approximately 3 to 5 meters in extreme cases. Soils are primarily of the Commerce silt loam and Sharkey clay series (Mr. Johnny Lack, Anderson-Tully Company, personal communication). Tree species composition is of the riverfront hardwood association including sugarberry (62 percent), sweet pecan (8 percent), boxelder (*Acer negundo*; 8 percent), American elm (*Ulmus americana*; 8 percent), green ash (3 percent), and Nuttall oak (Q. nuttallii, 2 percent).

Two treatments, clearcutting and selection cutting, were installed in the winter of 1995/1996. Each treatment, plus an unharvested control, were located on 20-hectare treatment plots and replicated three times in a partially randomized design (no two treatment plots could share a common border) for a study area of 180 hectares. In the clearcutting treatment, all commercial stems were removed during the logging operation. A followup treatment consisted of felling all stems ≥5 centimeters diameter at breast height (d.b.h.) to create a complete, or biological, clearcut. In the selection harvest, tree marking was done according to Anderson-Tully Company guidelines. Combinations of single-tree and group selection harvesting were conducted to remove approximately one-third to one-half of the basal area. Tree species favored for continued management included green ash, Nuttall oak, sweet pecan, and sugarberry.

Prior to harvest, sixteen 0.1-hectare circular plots were systematically established within each treatment plot. Within each 0.1-hectare plot, a 0.01-acre (0.004 hectare) circular regeneration plot was established, on either the east or west end of the larger plot. An English-unit plot dimension was necessary to test the regeneration results with a regeneration evaluation model recently developed for Coastal Plain bottomland hardwoods (Hart and others 1995). All seedlings ≥30 centimeters (1 foot) in height were measured for height, ground-line diameter, previous growing season linear stem growth, topographic location (ridge, swale, or transition between the two), and vigor (good, medium, or poor). These seedlings were also flagged and distance/azimuth measured for future relocation and measurement. First-year postharvest measurements were conducted during the winter of 1996/1997 (designated as 1996) and included any new seedlings in the ≥30 centimeters size class. Survival and density retention were calculated based on the two sets of measurements. Density retention was defined as the percentage of seedlings ≥30 centimeters tall in 1996 compared to those present in 1995. A density retention of 100 percent indicates 100 percent survival with no recruitment of new seedlings ≥30 centimeters tall, or the recruitment of new seedlings into this size class was equal to the mortality of seedlings measured prior to harvest. Data were analyzed using analysis of variance. Duncan's

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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

Survival and Density Retention

Survival rate of seedlings measured in 1995 was 39 percent. This low rate survival was the result of both harvesting and a June 1996 flood that inundated the site for 3 weeks. Harvesting effects were apparent as survival was lowest in the clearcuts (15 percent) and highest in the controls (68 percent) with the partial harvest having an intermediate value (35 percent) (table 1). A similar pattern of survival was reported by Lowe (1996) in the Neches River floodplain in east Texas. Surprising, though, was the low survival rate in the controls where no harvesting took place. Seedlings ≥30 centimeters were considered well-established, advanced regeneration; therefore, they were expected to have low mortality in the controls. Flooding during the 1996 growing season represented the fourth straight year of growing season flooding inside the levee system of the Mississippi River. These floods inundated seedlings after they had leafed out, placing them under considerable stress. Most of the seedlings measured prior to harvest were classed as poor in vigor, due probably to both low light levels and the previous three years of growing season flooding.

While survival was low, especially in the harvest treatments, density retention was good, indicating a high recruitment of seedlings into the ≥30 centimeters size class (table 1). Although not significantly different, a pattern of greater harvest intensity resulted in higher mean density retention. This pattern was the inverse of survival. Lowe (1996) also reported an inverse pattern between survival and density retention, with lowest survival and greatest density retention occurring in the greatest harvesting intensity (clearcuts). High rates of density retention were particularly evident with sugarberry, especially in the harvest treatments (table 2). Sugarberry is a noted root and stump sprouter following harvesting (Kennedy 1990). Care was taken during the 1996 measurements to use only the tallest seedling when multiple root and stump sprouts were present around individual sugarberry stumps. Numerous recent sugarberry germinates (usually 3 to 6 centimeters in height) were observed during the fall following the 1995 and 1996 growing seasons. Obviously, some of these seedlings and/or the seedlings germinating from buried seed following the June 1996 flood contributed to this high recruitment of sugarberry seedlings into the ≥30 centimeters size class. All other species with a least 20 seedlings per treatment plot showed a similar pattern of survival, but not density retention, as sugarberry (table 2). Noteworthy was the low survival of green ash, a premier timber species on the Mississippi Alluvial Plain.

Height and Linear Stem Growth

Average height of seedlings was 64 centimeters prior to harvest. Linear stem growth, which reflected the growth in stem length from the previous year's terminal bud, was 8 centimeters across the study site. This low stem growth is typical of advanced bottomland hardwood regeneration growing underneath closed canopies (Janzen and Hodges 1987, Lockhart and others 1991). Average seedling height was 51 centimeters 1 growing season after harvest (table 1). Reductions in seedling height from the previous growing season can be attributed to stem dieback and mortality. While actual seedling height decreased, linear stem growth tripled for seedlings growing in the harvesting treatments (table 1). Greater growth compared to controls was most likely due to the higher light levels reaching the forest floor and the greater vigor associated with root and stump sprouts.

CONCLUSIONS

Conclusions, based on 1-year postharvest results, are:

(1) harvesting does have an impact on regeneration survival and composition 1 year following harvesting,

Table 1—Survival, density retention, and linear stem growth (LSG) for seedlings ≥1 foot in height by harvest treatment on Pittman Island, Issaquena County, MS

		Harvest treatment		
Description	Unit	Clearcut	Selection	Control
Survival	Percent	15 a[a]	35 b	68 c
Density retention	Percent	142	90	73
Height (1995)	Centimeter	62	64	67
Height (1996)	Centimeter	48	52	52
LSG (1995)	Centimeter	8	9	7
LSG (1996)	Centimeter	34 a	32 a	10 b

[a] Numbers followed by different letters within a row are significantly different at the alpha=.05 level.

Table 2—Survival (Surv.) and density retention (DR.) for seedlings ≥30 centimeters in height for selected species by harvest treatment on Pittman Island, Issaquenna County, MS

	Harvest treatment					
	Clearcut		Selection		Control	
Species	Surv.	DR.	Surv.	DR.	Surv.	DR.
	Percent					
Sugarberry	16	224	34	129	73	75
Green ash	9	11	24	27	57	60
American elm	11	22	33	33	58	65
Deciduous holly	18	35	50	66	81	86
Swamp privet	5	47	50	69	93	93

(2) growing season flooding also appears to have an impact on advanced regeneration survival,
(3) sugarberry has the capacity to respond rapidly to harvesting, and
(4) 1-year postharvest results are probably not reliable to predict future regeneration composition in lands inside the levees of the Mississippi River.

ACKNOWLEDGMENT

The author would like to acknowledge Anderson-Tully Company for providing the land and technical assistance in this study, the Arkansas Forest Resources Center for providing the initial funding for this project, and Hal Liechty for providing a critical review of this manuscript. Published with the approval of the Director of the Arkansas Agricultural Experiment Station.

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AN EVALUATION OF HARDWOOD REFORESTATION METHODS ON PREVIOUSLY FARMED LANDS IN CENTRAL ALABAMA

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Abstract—First-year growth and survival of 1-0 oak seedlings were measured to determine the effectiveness of operational-scale mechanical subsoiling, planting methods, and grass control methods in establishing oak on previously farmed lands in central Alabama. First-year seedling height growth was improved by a mechanically subsoiled treatment. Machine-planted seedlings had significantly greater first-year growth and survival than hand-planted seedlings. A two-pass application of Fusilade 2000™ resulted in significantly greater first-year growth in height, and discing significantly increased first-year survival in a field that possessed a heavy grass sod.

INTRODUCTION

Bottomland hardwood forests are among the most productive timberland and wildlife habitats in the United States. This resource has numerous economic, ecological, and aesthetic values to society. The consumption of forest products has increased 140 percent since 1975, and hardwoods comprise about one-fifth of the 370 million cubic meters consumed annually in the United States (Anonymous 1997). Hardwood growth currently exceeds hardwood removals, but may not be readily available for harvests (Abt and others 1994).

Tremendous agricultural potential led to the clearing of about half the original eastern hardwood forest by the late 1930's, and the pace of clearing hardwood bottomlands escalated throughout the 1970's. Many of these hardwood bottomlands were better suited for forest than for agriculture because of periodic inundation (Allen and Kennedy 1989). Currently, there are opportunities to reforest these agricultural lands on a cost-share basis under the auspices of the Farm Bill and its amendments. In the South, about 73,700 hectares have been enrolled for reforestation under State and Federal cost-share programs, and it is projected that as many as 110,000 hectares will be reforested by the year 2005.[2]

Artificial regeneration is the only means of establishing oak on areas that are void of an existing oak component. In the South, artificial regeneration implies either direct seeding or seedling planting (Kennedy 1992), but there is limited information regarding the ensured, future success of bottomland oak species on agricultural lands. The establishment method is complex and several years may elapse before planting success can be adequately appraised. Development and evaluation of practical oak reforestation techniques are needed (Lea and Fredrick 1989).

The fracturing of a soil hardpan by mechanical subsoiling or discing is an effective means of increasing tree growth by mitigating the adverse effects of soil compaction (Woodrum 1982, Morris and Lowery 1988, Nix 1989), a phenomenon commonly associated with heavy equipment trafficking. Subsoiling increases the amount of soil exploited by seedling roots, results in greater uniformity of seedling depth, and may increase soil moisture availability (Miller 1992). Increased planting uniformity reportedly increases the survival of machine-planted pine seedlings as compared to hand-planted pine seedlings (South and Mexal 1984). Studies are inconsistent with respect to which of the two planting methods is generally best as a means of establishing pine (*Pinus* spp.) (Wakely 1954, McNab and Bredemuehl 1983, Xydius and others 1983). Ninety-one percent of nonindustrial and public plantings are currently performed by independent contractors (Long 1991).

Interference from competing vegetation may be the most consistent factor contributing to oak establishment failures on old field sites (Bey and others 1975, von Althen 1977). Increased early growth rates of oaks after vegetation control have been noted (Aust and others 1985, Krinard and Kennedy 1987).

The purpose of this research was to evaluate mechanical subsoiling, hand and machine planting, and techniques of controlling competing vegetation on fields with heavy grass sods as suitable methods of reforesting recently abandoned farmlands to oak. This study was comprised of three independent experiments that were conducted on an operational basis.

METHODS

The study was incorporated into a planting activity encompassing approximately 1,011 ha that is part of the Tennessee Tombigbee Waterway Wildlife Mitigation Project administered by the U.S. Army Corps of Engineers. The study area was located in the Alluvial Floodplains Province and surrounded by the Hilly Coastal Plains Province (Hodgkins and others 1976) in northeastern Lowndes County, near Whitehall, AL. Primary land-use prior to 1996

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consisted of cotton production. Fallow cotton fields, hay fields, and forestland comprised remaining land usages.

Operational-scale treatments consisted of mechanical subsoiling, discing, two-pass herbicide applications, and machine seedling plantings. Operational-scale treatments were performed by an independent contractor under agreement with the State of Alabama Department of Conservation and Natural Resource Game and Fish Division. Experimental plot size was 1616 square meters. Seedlings were spaced on a 3.66-meter grid. Plot size and seedling spacing facilitated the planting of 100 seedlings per plot, but only the interior 64 seedlings were measured to eliminate edge bias. Response variables were seedling growth in height and diameter, and percent survival. Preseason seedling heights and diameters were measured prior to active stem growth in the third week of April 1996. Postseason seedling heights and diameters were measured in the fourth week of September 1996.

Subsoiling Experiment

The mechanical subsoiling experiment was located in a former cotton field on an upland site with Bama soil series (fine-loamy, silicous, thermic Typic Paleudults). The site possessed a traffic pan within 30.5 centimeters of the soil surface. Experimental plots were arranged in a split-plot design. Mechanical subsoiling and control comprised whole-plot experimental treatments. Split-plot experimental variables consisted of machine-planted 1-0 cherrybark oak (*Quercus pagoda*), water oak (*Q. nigra*), and white oak (*Q. alba*) bareroot seedlings. Treatments were randomly assigned to experimental plots, and each treatment combination was replicated four times. The ripping procedure was implemented by welding a metal shank about 61 centimeters in length to the trencher of a continuous-furrow mechanical tree planter and traversing the site 6 weeks prior to planting. Treatment seedlings were planted directly into the subsoiled trench.

Planting Method Experiment

A factorial design was used to compare the effectiveness of hand and machine planting methods. Experiment treatments consisted of topographic site, oak species, and planting method. Soils at the upland site are of the Bama soil series. The terrace site consisted of Annemaine soil series (clayey, mixed, thermic Aquic Hapludults). Soils at the floodplain site were of Izagora soil series (fine-loamy, silicous thermic Aquic Paleudults). Seedlings were 1-0 bareroot cherrybark and water oak. Treatments were randomly assigned to experimental plots and each planting method-species combination was replicated three times on the upland, terrace, and floodplain sites. Machine and hand plantings were performed January-February 1996.

Grass Control Experiment

A completely randomized design was used to evaluate techniques for controlling competing vegetation on a hayfield site that had a heavy grass sod. The experiment was situated on a low terrace site with Annemaine soil series. Experimental treatments were discing immediately prior to planting, a one-pass over-the-top band application of Fusilade 2000™ in June, discing before planting and a one-pass over-the-top band application of Fusilade 2000™ in June, a two-pass over-the-top band application of Fusilade 2000™ in June and again in July, and an experimental control. Herbicide application rate was 2.62 liters of Fusilade 2000™ per hectare with an 80 percent nonionic surfactant. The two-pass herbicide treatment was replicated three times. All other treatments were replicated four times. Seedlings were machine planted and consisted entirely of 1-0 bareroot cherrybark oak.

RESULTS

Subsoil Experiment

Preseason seedling heights were greater ($p = 0.0129$) in the control than in the subsoil treatment. Mean preseason height of treatment seedlings was 34.8 centimeters versus 36.7 centimeters for control seedlings. Mechanical subsoiling increased ($p = 0.0155$) the first-year height growth of oak seedlings. First-year seedling diameter growth and percent survival did not differ ($p = 0.0919$ and $p = 0.9188$, respectively) between treatments. First-year height growth of cherrybark oak seedlings was greater ($p = 0.0317$) in the mechanical subsoil treatment than in control. First-year height growth of water oak ($p = 0.0518$) and white oak ($p = 0.0892$) did not differ between treatments (table 1).

Planting Methods Experiment

Machine-planted seedling heights (mean = 42.1 centimeters) were greater ($p = 0.0066$) than hand-planted seedling heights (mean = 36.8 centimeters) at preseason sampling. Machine planting increased the first-year height growth ($p = 0.0002$), first-year diameter growth ($p = 0.0013$), and first-year survival ($p = 0.0001$) of cherrybark and water oak seedlings (table 2). Average height growth was lower on the terrace site (mean = 9.8 percent) than on the upland (mean = 34.2 percent) and floodplain (mean = 25.3 percent) sites. Mean diameter growth differed among upland (mean = 72.9 percent), terrace (mean = 24.6 percent), and floodplain (mean = 51.7 percent) sites.

Percent diameter increase of water oak was greatest on upland and floodplain sites. Percent diameter increase of cherrybark oak was greater ($p = 0.0077$) on the upland than on the floodplain site. Water oak did not exhibit differential survival among topographic sites, but survival of cherrybark oak was less ($p = 0.0019$) on the upland than on the floodplain and terrace sites. Survival of water oak seedlings was generally greater than survival of cherrybark oak seedlings.

Machine planting resulted in greater ($p = 0.0169$) seedling survival on the upland and terrace sites than did hand planting, but seedling survival did not differ significantly between planting methods on the floodplain site. Machine-planted water oak had greater survival than hand-planted water oak, and machine-planted cherrybark oak had greater survival than hand-planted water oak. Hand-planted water oak had greater ($p = 0.0006$) survival than hand-planted cherrybark oak. No differential survival was detected between hand-planted water and machine-planted cherrybark oak seedlings (fig. 1).

Table 1—First-year height growth (cm), diameter growth (mm), and percent survival (mean ± standard error) of 1-0 cherrybark, water, and white oak seedlings in response to mechanical subsoiling; relative percent height growth and percent diameter growth are in parentheses; means in a row with unlike letters differ significantly at the 0.05 probability level

Response	Subsoil treatment	Control
Cherrybark oak		
Height growth	11.9 ± 0.68	7.7 ± 1.0
	(35.6 ± 1.8)a	(21.3 ± 2.9)b
Diameter growth	2.8 ± 0.21	2.4 ± 0.4
	(59.3 ± 3.5)a	(54.7 ± 8.7)a
Survival	73.5 ± 2.72a	74.8 ± 3.8a
Water oak		
Height growth	26.9 ± 3.0	16.5 ± 1.8
	(70.3 ± 8.8)a	(39.7 ± 3.9)a
Diameter growth	5.7 ± 0.8	4.1 ± 0.3
	(139.3 ± 23.5)a	(91.1 ± 6.4)a
Survival	96.4 ± 0.4a	94.0 ± 1.5a
White oak		
Height growth	18.6 ± 2.5	14.4 ± 1.3
	(57.8 ± 8.5)a	(44.7 ± 4.8)a
Diameter growth	4.5 ± 0.7	3.6 ± 0.4
	(99.8 ± 18.1)a	(85.2 ±
12.2)a		
Survival	98.4 ± 0.6a	98.8 ± 1.2a
Total		
Height growth	19.2 ± 2.2	12.9 ± 1.3
(54.5 ± 5.7)a	(35.2 ± 3.6)b	
Diameter growth	4.4 ± 0.5	3.4 ± 0.3
(99.5 ± 13.3)a	(77.0 ± 6.9)a	

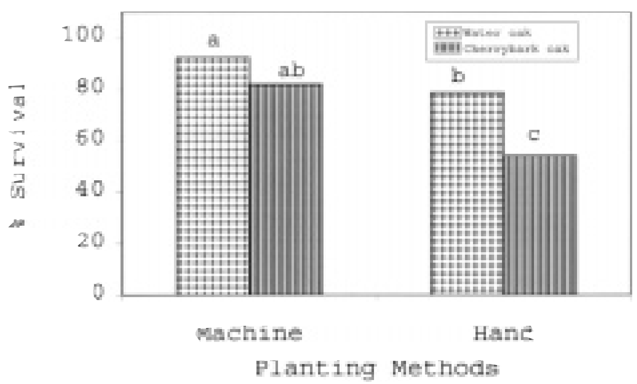

Figure 1—First-year survival of cherrybark and water oak seedlings in machine- and hand-planting treatments in central Alabama. Survival means with unlike letters differ significantly at the 0.05 probability level.

Grass Control Experiment

Pre-season seedling heights were greater ($p = 0.0001$) in disced (alone [mean = 33.3 centimeters] and in combination with one-pass herbicide treatment [mean = 33.4 centimeters]) plots than in two-pass herbicide plots (mean = 29.5 centimeters). The application of a split, two-pass herbicide treatment resulted in greater ($p = 0.0064$) first-year height growth than other grass control methods and control. Discing, alone and in combination with one-pass herbicide treatment, resulted in greatest ($p = 0.0023$) first-year seedling survival. First-year seedling survival did not significantly differ among one- and two-pass herbicide treatments and control (table 3). However, actual percent seedling mortality that had occurred prior to the implementation of herbicide treatments was not documented, and it is possible that seedling mortality had occurred prior to chemical treatment application.

Table 2—First-year height growth (cm), diameter growth (mm), and survival (mean ± standard error) of hand- and machine-planted 1-0 cherrybark and water oak; relative percent height growth is in parentheses; growth means in a row with unlike letters differ significantly at the 0.05 probability level

	Planting method	
Response	Hand	Machine
Height growth (cm)	4.9 ± 1.6	12.8 ± 2.4
	(11.9 ± 3.4)a	(34.4 ± 6.5)b
Diameter growth (mm)	1.7 ± 0.3	2.7 ± 0.4
	(38.1 ± 7.9)a	(61.5 ± 8.9)b
Percent survival	59.8 ± 4.9a	87.0 ± 2.3b

DISCUSSION

Mechanical subsoiling significantly increased seedling height growth. Diameter growth increased at the 0.10 probability level, but mechanical subsoiling did not affect first-year seedling survival. Increased height and diameter growth on this upland site is attributed to the disruption of the existing traffic pan and to increased planting depth, both of which may have increased exploitable soil, increased moisture availability, and subsequently increased root growth and development. Apparently, moisture stress was not so severe as to limit first-year seedling survival. After three years, Miwa and Schoenholtz[3] observed no difference between Nuttall oak (*Q. nuttallii*) seedling growth in mechanically subsoiled and control treatments on a Mississippi alluvial floodplain site, because moisture availability may generally be much greater on floodplain than on terrace and upland sites. Mechanical subsoiling may be neither appropriate nor necessary in all instances.

Increased first-year height and diameter growth of machine-planted seedlings can be attributed to greater planting depth, as confirmed by significantly lower

[3] Personal communication. 1997. Stephen Schoenholtz, Associate Professor, Mississippi State University, Mississippi State, MS 39762.

Table 3—First-year height growth (cm), diameter growth (mm), and survival (mean ± standard error) of 1-0 cherrybark oak seedlings after grass control treatments; means in a column with unlike letters differ significantly at the 0.05 probability level

Treatment	Height growth	Height change	Diameter growth	Diameter change	Survival rate
	cm	*Percent*	*Mm*	*Percent*	*Percent*
Disc	-0.1 ± 1.0	-0.1 ± 1.0a	0.6 ± 0.2	13.1 ± 4.9a	78.5a
1-herbicide[a]	1.87 ± 1.1	5.8 ± 3.3a	5.8 ± 3.3	17.2 ± 6.1a	52.8b
2-herbicide[b]	5.20 ± 1.1	18.5 ± 5.3b	—-	—-	46.6bc
Disc and herbicide	0.66 ± 0.3	1.93 ± 1.0a	0.49 ± 0.1	11.2 ± 3.3a	71.0a
Control	1.25 ± 0.4	4.12 ± 1.3a	0.46 ± 0.3	10.5 ± 7.0a	52.9bc

[a] Treatment consists of a one-pass application of Fusilade 2000™.
[b] Treatment consists of a split, two-pass application Fusilade 2000™ performed by State of Alabama planting contractor.

preseason seedling heights and diameters, and to the greater planting uniformity afforded by the mechanical planter, both of which potentially increase soil moisture availability. Soils on terrace sites usually have well developed agrillic and fragipan horizons. The growth and development of hardwoods are generally not as good on these as on floodplain sites due to the inherent leaching of nutrients, the presence of a well-developed fragipan, and less favorable soil moisture conditions (Hodges 1995). Relative to the floodplain and terrace sites, less competing vegetation was observed on the upland site. Significantly less seedling growth on the terrace than on the upland and floodplain sites was expected. Differential survival of cherrybark oak among topographic sites may underscore the site-specific sensitivity of this species.

Light is a dominant limiting factor for oak development under dense forest canopies, but soil moisture may also limit oak establishment (Hodges and Gardiner 1992). Crow (1988) identified "large, well-developed, well-established" root systems as the key factor to rapid seedling growth, and other studies have demonstrated the responsiveness of oak seedlings to soil moisture stress (Larson and Whitmore 1970, Larson 1980).

Discing, alone or in combination with a single herbicide application, increased first-year survival. The split, two-pass herbicide treatment, however, resulted in about twice the first-year height growth of seedlings than in any other grass control treatment. Zutter and others (1986) report soil moisture and first-year height and diameter growth of loblolly pine as negatively correlated with the level of herbaceous vegetation, and first-year pine growth most highly correlated to soil moisture level in late August when soil moisture was lowest. Mechanical alteration of the heavy grass sod by discing may have created a soil environment favorable to early-season root development. Both the increased survival of seedlings in disced plots, and the increased height growth of seedlings in the split, two-pass herbicide treatment are attributed to increased moisture availability. The striking differences in seedling response between these two treatments, however, possibly reflects the timing of competing vegetation removal.

CONCLUSIONS

In this study, increased mechanical manipulation of the soil improved seedling growth. It is suggested that one reason for improved growth is greater moisture availability due to greater planting depths in the subsoiled areas and by machine planting. In addition, this study demonstrates that mechanical subsoiling, machine planting, and grass control techniques may be practical methods of establishing oak on previously farmed lands on an operational scale.

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INFLUENCE OF SOIL SERIES AND PLANTING METHODS ON FIFTH-YEAR SURVIVAL AND GROWTH OF BOTTOMLAND OAK RE-ESTABLISHMENT IN A FARMED WETLAND

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Abstract—Bottomland hardwood forest restoration often depends on reestablishment of bottomland oak species. Success, using either planted seedlings or acorns, has been inconsistent and may require several years before it can be accurately assessed. In 1991, a study was initiated on a farmed wetland in the Lower Mississippi Alluvial Valley to evaluate effects of soil series and planting methods on reestablishment of cherrybark oak (*Quercus pagoda* Raf.), Nuttall oak (*Quercus nuttallii* Palmer), Shumard oak (*Quercus shumardii* Buckl.), and water oak (*Quercus nigra* L.). A randomized complete block design with four replications was used to test performance of the four oak species established by direct seeding or planting of bareroot seedlings on three common soil series (Sharkey, Forestdale, and Dundee). Overall survival and growth after five growing seasons was not affected by soil series. Survival of trees originating from planting as bare-root seedlings was significantly greater than that for trees direct-seeded for Nuttall, cherrybark and water oaks, whereas for Shumard oak there was no significant difference between planting methods. Height and groundline diameter of trees planted as bare-root seedlings after 5 years was greater than height of direct-seeded trees for all four oak species. After 5 years, Nuttall oak had a 72 percent overall survival rate, mean height of 169 centimeters, and mean groundline diameter of 27 millimeters; followed by water oak (59 percent, 115 centimeters, and 15 millimeters); Shumard oak (55 percent, 76 centimeters, and 11 millimeters); and cherrybark oak (52 percent, 67 centimeters and 10 millimeters). Survival of each species, whether planted as bare-root seedlings or by direct seeding, produced stocking that surpassed Federal Wetland Reserve Program standards for tree reestablishment. This suggests that mixed-species plantings using these four oak species can be successfully established on sites with similar soils and hydrologic conditions.

INTRODUCTION

The importance and multiple values of forested wetlands have generally been recognized only within the past 2 decades (Mitsch and Gosselink 1993). Studies show that in most of the United States more wetland area was destroyed than was required to be restored or created, resulting in net losses of these valuable ecosystems (Kentula and others 1993). For example, about 2.4 million hectares of forested wetlands were converted to other land uses (mainly agriculture) in the United States between 1950 and 1970 (Lugo and others 1990). Loss of bottomland hardwood (BLH) forests in the Lower Mississippi River Alluvial Valley (LMAV) is estimated at about 6.5 million hectares since European settlement, and most of the remaining BLH forests in LMAV are fragmented and have lost many of their original values (Mitsch and Gosselink 1993). Almost 12.4 million hectares, less than one-third of that prior to European settlement, of forested wetlands remain in the South with about 2 million in the floodplain of the LMAV (Stanturf and Shepard 1995). Rudis (1995) stated that clearing of forested wetlands for nonforest land use is frequently done because of their suitable agricultural conditions, including rich alluvial soils and adequate moisture.

This large amount of loss has caused increasing efforts to restore and protect wetlands in recent years (Mitsch and Gosselink 1993). Since 1980, numerous restoration and protection projects have been supported by both public and private programs. These include the Conservation Reserve Program and the Wetland Reserve Program (WRP). The purpose of these programs is to establish an adequate vegetative cover in fragmented ecosystems and to mitigate fish and wildlife habitat losses (Stanturf and Shepard 1990). The LMAV has the most restoration projects applied to former BLH forest sites that were cleared since the 1950’s and converted to farmland (Clewell and Lea 1990). However, according to Clewell and Lea (1990), there have been relatively few intentional creation or restoration efforts to compensate for lost forested wetlands in the Southeastern United States, and most of them are too young to be assessed. In addition, some limitations need to be addressed for successful efforts on restoration of BLH forests. Allen and Kennedy (1989) mentioned the following problems identified from BLH forest restoration projects: (1) site selection and the possible need for site preparation, (2) the question of which species on which type of soil, and (3) choosing a planting technique—direct seeding or planting of seedlings. Furthermore, Hook (1987) explained that relationships between hydroperiod and site requirements of some species, including oaks and other heavy-seed species that inhabit mixed BLH wetlands, are not well understood. These limitations and lack of information on restoration suggest a need for information related to species-site interactions and choice of planting methods. The overall objective of this study is to assess impacts of soil series and planting methods on fifth-year survival and growth of four bottomland oak species in a reestablishment effort in the LMAV.

METHODOLOGY

This study is located in Yazoo County, MS, and is a part of the Lake George Wildlife Wetland Restoration Project established by the U.S. Army Corps of Engineers in 1991. It comprises about 3,300 hectares that were originally forested and are being incrementally replanted with trees to replace crop production. The project site is bounded by two

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fragmented forest ecosystems: the Delta National Forest and the Panther Swamp National Wildlife Refuge. One of the major objectives of the overall Lake George Project is to reestablish a BLH forest in order to connect these two fragmented forests.

Three soil series that commonly occur in the LMAV were evaluated in this study: (1) Dundee (fine-silty, mixed, thermic, Aeric Ochraqualfs) soils are at the higher elevations and have a brown surface soil and a brownish silty clay subsoil, (2) Forestdale (fine, montmorillonitic, thermic, Typic Ochraqualfs) soils are at lower elevations than Dundee soils and are grayer and more poorly drained than Dundee soils, and (3) Sharkey (very fine, montmorillonitic, nonacid, thermic, Vertic Haplaquepts) soils are at lowest elevations, are poorly drained, and have dark-colored, clayey profiles (Scott and others 1975). Miwa (1993) has reported physical and chemical properties of these soil series as they occur at the study site.

Four bottomland oak species commonly used on restoration and reforestation projects in the South were evaluated: cherrybark oak (*Quercus pagoda* Raf.), Nuttall oak (*Quercus nuttallii* Palmer), Shumard oak (*Quercus shumardii* Buckl.), and water oak (*Quercus nigra* L.). Water oak, cherrybark oak, and Shumard oak are desirable species that can be regenerated on the ridges in bottomlands, whereas Nuttall oak is suitable in the flats of bottomlands (Ezell and Hodges 1994). Seedlings grown in the nursery for 1 year were obtained from Delta View Nursery in Leland, MS, and from the Mississippi Forestry Commission Nursery in Winona, MS. They were hand-planted at 3 by 3 meter spacing in December 1991 (Miwa 1993). Acorns of cherrybark, Shumard, and water oak were collected near Starkville, MS, whereas Nuttall oak acorns were collected in the Mississippi Delta region. All acorns were hand-planted at 3 by 3 meter spacing with two acorns per location at a depth of 5 to 8 centimeters in March 1992 (Miwa 1993). Survival, height, and groundline diameter were measured at the end of the first and second growing seasons, in 1992 and 1993, respectively, and reported by Miwa (1993). Fifth-year survival, height, and groundline diameter were measured in October 1996.

A randomized complete block design with split-split plots was applied to compare treatments. Four blocks (replications) were established at the restoration site. Treatments within this design were as follows: (1) main treatment plots made up of one of three common soil series (Dundee, Forestdale, and Sharkey), (2) four oak species (cherrybark oak, Nuttall oak, Shumard oak, and water oak) randomly assigned to split plots, and (3) two planting methods (direct seeding and seedling planting) randomly assigned as split-split plots. Analysis of variance (ANOVA) was used to test null hypotheses at the 0.05 significance level. (Schlotzhauer and Littell 1987). To compare our treatment means, ANOVA with Least Significant Difference (LSD) to test for means separation was used. Arcsin transformations were applied to survival data to normalize their distributions (Aster and Seidman 1991).

RESULTS AND DISCUSSION

Effects of Soil Series

Fifth-year survival of cherrybark, Nuttall, Shumard, and water oaks was not affected by soil series (table 1). Survival pooled across both planting methods ranged from 50 percent for cherrybark oak on Dundee soils to 73 percent for Nuttall oak on Sharkey soils (table 1). These survival rates, which are pooled for seedlings and acorns planted on 3 by 3 meter spacing, result in fifth-year stocking that ranges from 556 trees per hectare for cherrybark oak on Dundee soils to 811 trees per hectare for Nuttall oak on Sharkey soils. This range exceeds the required 309 trees per hectare for satisfactory stocking of BLH species on WRP restoration sites at the end of three growing seasons. Lack of soil series effects suggests that differences in soil physical and chemical properties among the three soil series reported by Miwa (1993) did not significantly influence survival of oak species after 5 years.

Height and groundline diameter were not different among the three soil series after 5 years for Nuttall, Shumard, and water oak (table 1). However, for cherrybark oak, height (83 centimeters) and groundline diameter (12 millimeters) on Sharkey soil were significantly larger than height (46 centimeters) and groundline diameter (6 millimeters) on Forestdale soil, but did not differ significantly from height (73 centimeters) or groundline diameter (11 millimeters) on Dundee soil (table 1). The relatively strong performance of cherrybark oak on Sharkey soil was unexpected. Krinard (1990) stated that cherrybark oak develops best on loamy,

Table 1—Effect of soil series on fifth-year survival and size of four planted oak species at the Lake George Wetland Restoration Site in Yazoo County, MS[a]

	Oak species			
Soil series	Cherrybark	Nuttall	Shumard	Water
Survival rate (pct)				
Dundee	50 a[b]	69 a	55 a	58 a
Forestdale	52 a	73 a	57 a	63 a
Sharkey	53 a	73 a	54 a	57 a
Height (cm)				
Dundee	73 ab	189 a	86 a	130 a
Forestdale	46 b	142 a	65 a	94 a
Sharkey	83 a	177 a	75 a	121 a
Diameter (mm)				
Dundee	11 ab	30 a	14 a	17 a
Forestdale	6 b	23 a	10 a	13 a
Sharkey	12 a	27 a	11 a	15 a

[a] Values are means of four plots.
[b] For each oak species and response variable, means followed by different letters are significantly different at the 0.05 level according to Fisher's protected LSD test.

well-drained soil and is uncommon on clay soil such as Sharkey, which is poorly drained. Our results suggest that moisture relations on Sharkey soil at this site did not differ as a limiting factor for oak survival or growth compared with moisture relations on Dundee or Forestdale soils. Furthermore, flooding has not been observed on the study plots, suggesting that excess water and poor drainage often associated with Sharkey soils did not occur on this site.

Effects of Planting Method

Evaluation of planting-method effects was pooled across soil series because there was no interaction between planting method and soil series. Survival of planted seedlings of cherrybark, Nuttall, and water oak was 74, 79, and 67 percent, respectively, and was significantly higher than 29, 65, and 51 percent survival, respectively, resulting from direct seeding (table 2). Similarly, fifth-year survival of planted seedlings of Shumard oak was 61 percent compared with 50 percent for seedlings from direct seeding. However, this difference was not significant at the 0.05 level. These results show the consistent advantage of planted seedlings for enhanced survival when compared with direct seeding. However, even direct-seeded cherrybark oak with 29 percent survival produced a stocking of 322 trees per hectare, which is greater than minimum stocking requirements for WRP sites.

Fifth-year height and diameter were significantly greater on planted seedlings than on seedlings from direct-seeded acorns among all four oak species (table 2). Mean height and diameter of planted cherrybark, Shumard, and water oak seedlings were at least three times greater than seedlings from direct seeding, whereas size of planted Nuttall oak seedlings was approximately two times greater than seedlings from direct seeding (table 2). Allen (1989) conducted a study using Nuttall, water, Shumard, and cherrybark oak species in the Yazoo National Wildlife Refuge Complex in Washington County, MS, and found that both height and diameter growth of planted seedlings were higher than for seedlings from direct seeding. Stanturf and Kennedy (1996) also reported that planted seedlings of cherrybark oak were significantly larger than direct-seeded cherrybark oak seedlings after 5 years.

Table 2—Effect of planting method on fifth-year survival and size of four planted oak species at the Lake George Wetland Restoration Site in Yazoo County, MS[a]

Planting Method	Oak species: Cherrybark	Nuttall	Shumard	Water
Survival rate (pct)				
Planted seedling	74 a[b]	79 a	61 a	67 a
Direct seedling	29 b	65 b	50 a	51 b
Height (cm)				
Planted seedling	102 a	215 a	114 a	182 a
Direct seedling	33 b	124 b	37 b	48 b
Diameter (mm)				
Planted seedling	15 a	38 a	18 a	25 a
Direct seedling	4 b	16 b	5 b	6 b

[a] Values are means of four plots.
[b] For each species and response variable, means followed by different letters are significantly different at the 0.05 level according to Fisher's protected LSD test.

Comparison of Species

Species comparisons of survival, height, and groundline diameter were pooled across soil series since there was not a species-soil series interaction. Nuttall oak had the highest fifth-year survival and largest size for either of the two planting methods (table 3). For planted seedlings, Nuttall oak had 79 percent survival followed by cherrybark, water, and Shumard oak with 74, 67, and 61 percent survival, respectively. For direct seeding, Nuttall oak had 65 percent survival followed by water, Shumard, and cherrybark oak with 51, 50, and 29 percent, respectively (table 3). This result concurs with other studies that have compared oak species for artificial regeneration of BLH forests (Johnson and Krinard 1988, Johnson and Krinard 1989).

Fifth-year height and groundline diameter of Nuttall oak for both planted seedlings and seedlings from direct seeding were significantly greater than the other three species (table 3). Trees originating as planted seedlings had heights

Table 3—Comparison of fifth-year survival and size of four oak species using two planting methods at the Lake George Wetland Restoration Site in Yazoo County, MS[a]

Oak species	Planted seedling	Direct seeding
Survival (pct)		
Cherrybark oak	74 a[b]	29 c
Nuttall oak	79 a	65 a
Shumard oak	61 b	50 b
Water oak	67 ab	51 b
Height (cm)		
Cherrybark oak	102 c	33 c
Nuttall oak	215 a	124 a
Shumard oak	114 c	37 bc
Water oak	182 b	48 b
Diameter (mm)		
Cherrybark oak	15 c	5 b
Nuttall oak	38 a	16 a
Shumard oak	18 c	5 b
Water oak	25 b	6 b

[a] Values are means of four plots.
[b] For each planting method and response variable, means followed by different letters are significantly different at the 0.05 level according to Fisher's protected LSD test.

of 215 > 182 > 114 = 102 centimeters for Nuttall, water, Shumard, and cherrybark oak, respectively. Trees originating from direct seeding had heights of 124, 48, 37, and 33 centimeters for Nuttall, water, shumard, and cherrybark oak, respectively (table 3). Groundline diameter for planted and direct-seeded oak species followed the same patterns as height (table 3).

These results indicate that Nuttall oak has the most successful establishment and growth 5 years after planting on this site. This supports findings that Nuttall oak grows well on alluvial clay soils in the LMAV region (Filer 1990). However, cherrybark, Shumard, and water oak have adequate survival to meet the WRP stocking goal of 309 trees per hectare for both planted seedlings and seedlings originating from direct seeding. The slower growth rate of these three species in comparison to Nuttall oak indicates that they are not as well adapted as Nuttall oak to soil conditions on this site.

CONCLUSIONS

Based on fifth-year survival and size, Nuttall, cherrybark, Shumard, and water oak can be grown on any of the three soil series studied on this site, since soil series did not significantly affect measured response variables of the oak species. This result indicates that mixed-species plantings using these four oak species can be successfully established on similar sites. However, Nuttall oak showed best survival, height, and groundline diameter among the four species for either planting method. Furthermore, flooding has not occurred on this site during the course of this study and has, therefore, not been a limiting factor in association with poorly drained Sharkey soils.

Planted seedlings had better survival and size than seedlings established by direct seeding, suggesting that maximum establishment success and growth rates can be achieved with planted seedlings. However, direct-seeded seedling survival was sufficient to produce adequately stocked 5-year-old stands of all species according to WRP standards. This suggests that direct seeding can be successful on sites similar to this study if rapid early growth rate is not a primary objective.

ACKNOWLEDGMENT

Special thanks go to Janet Dewey for her assistance in the field and laboratory.

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POCOTALIGO SWAMP FOREST PLANTING DEMONSTRATION PROJECT

William H. Conner, Roy Todd, and L. Wayne Inabinette[1]

Abstract—Prior to logging in the late 1950's and 60's, the Pocotaligo Swamp represented a typical baldcypress-water tupelo (*Taxodium distichum-Nyssa aquatica*) riverine forest in south-central South Carolina. Regeneration of the swamp forest following logging was poor, due to permanent flooding conditions caused by logging access roads and the dense, mat-like growth of aquatic vegetation that occurred throughout the swamp. Efforts have been undertaken to restore portions of the swamp near Manning, SC. Three hundred fifty baldcypress seedlings were planted at four sites in May 1995. First-year survival was 76 percent and average height growth was 20 centimeters. Second-year survival was 64 percent and average height growth was 50 centimeters. In January 1996, an additional 249 root-pruned baldcypress and 73 containerized water tupelo were planted in three of the areas. Survival of the 1996 planted baldcypress was 80 percent and average height growth was 44 centimeters. Sixty-three percent of the water tupelo survived with an average height growth of 25 centimeters. Indications are that baldcypress and water tupelo can be successfully planted in the Pocotaligo Swamp if they can be protected from beaver herbivory. Long-term monitoring of these seedlings, along with additional plantings, will provide valuable information on restoration of flooded freshwater wetland sites.

INTRODUCTION

Forested wetlands were once viewed as obstacles to development, reservoirs of disease, and haunts of terrible monsters (Hammer 1997). Even with these perceptions, however, Europeans quickly recognized that cypress (refers to both baldcypress [*Taxodium distichum* (L.) Rich] and pondcypress (*T. distichum* var. *nutans*) when used like this) wood was very rot resistant, strong, and easily worked, and efforts to establish a timber trade with Louisiana began around 1700 (Mancil 1980). Harvesting in these wet swamps was seasonal in nature until the invention of the pullboat in 1889. Pullboats and the expansion of the railroad system (Sternitzke 1972), combined with a massive national campaign by cypress dealers (Burns 1980), resulted in a logging boom during the period 1890 to 1925. Production of cypress lumber increased from 1.17 million m^3 in 1899 to over 2.36 million m^3 in 1913 (Mattoon 1915, Betts 1938). By 1925, nearly all of the virgin timber had been cut and most of the mills closed. In 1933, only about 10 percent of the original standing stock of cypress remained (Brandt and Ewel 1989), but some cypress harvesting continued throughout the Southern United States on a smaller scale.

The Pocotaligo Swamp, located in Clarendon and Sumter Counties, SC, is a 12,141- hectare braided stream system once dominated by baldcypress and water tupelo (*Nyssa aquatica* L.) forests. In the 1950's and early 1960's, most of the swamp was logged. Numerous access roads were constructed to remove the timber, criss-crossing the swamp in numerous places and blocking stream channels. Normal water flow patterns were disrupted and much of the swamp became permanently flooded. Although baldcypress and water tupelo can both survive and grow in flooded areas (Brown 1981, Conner and others 1981, Wilhite and Toliver 1990), their seeds do not germinate under flooded conditions, and young seedlings are killed by a few days of submergence (Demaree 1932). As a result, much of the Pocotaligo Swamp never returned to a closed canopy forest but is now dominated by scrub-shrub stands with scattered trees. Freshwater marsh communities composed of pennywort (*Hydrocotyle ranunculoides* L.), cattail (*Typha latifolia* L.), and alligatorweed [*Alternanthera philoxeroides* (Mart.) Gris.] cover the swamp floor.

The Pocotaligo Swamp Restoration Committee was created in 1988 to provide leadership in the restoration of the swamp's natural ecosystem. In 1994, demolition experts blew 115 channel gaps in the old access roads, thus improving water flow in the swamp and lowering water levels approximately 1 foot. Planting began in 1995 in an effort to show landowners that trees could be planted in the swamp to restore the area to its former forested condition. This paper describes the preliminary efforts to reestablish baldcypress and water tupelo in the swamp.

METHODS

Four areas were selected in the upper Pocotaligo Swamp north of Manning for planting. In May 1995, a total of 357 baldcypress seedlings was planted at these sites. The seedlings were 2-year-old bareroot stock from the South Carolina Forestry Commission and were planted with a dibble in 2 to 3 feet of standing water. In January 1996, an additional 249 two-year-old baldcypress seedlings and 73 containerized water tupelo seedlings were planted in two of the areas. Because of the difficulty of planting seedlings in standing water, the baldcypress seedlings were root-pruned (lateral roots removed and the tap root cut at 8 inches) and planted by pushing the tap root into the soft sediment. Numbered, half-inch PVC pipe sections were used to mark the location of each seedling. Height measurements were made for each seedling when planted and at the end of the 1995 and 1996 growing seasons.

RESULTS AND DISCUSSION

First-year survival of baldcypress was similar for the 1995 planting (76 percent) and the 1996 planting (80 percent; table 1), indicating that root pruning was not detrimental to

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Table 1—Survival and height of baldcypress and water tupelo seedlings planted in Pocotaligo Swamp, SC

Year planted	Species	Survival rate 1995	Survival rate 1996	Height 1995	Height 1996
		- - - -*Percent*- - -		- - - - - - *Centimeters* - - - - - -	
1995	Baldcypress	76	64	96 (1.2)[a]	146 (2.5)
1996	Baldcypress	—	80	–	110 (2.2)
1996	Water tupelo	—	63	—	86 (3.4)

[a] Number in parentheses represents ± 1 SE.

seedling survival. Survival of water tupelo seedlings (63 percent) was less than that of baldcypress and may have been due the smaller size of the container-grown seedlings (starting height of 68 centimeters vs. 86 centimeters for baldcypress) and the deep water in which they were planted. Second-year survival of the 1995-planted baldcypress declined to 64 percent, mainly as a result of beaver clipping the seedlings. Beaver moved into the area in 1996, and freshly cut seedlings were observed when the height measurements were made. Other researchers in South Carolina have had similar problems with beaver (McLeod and others 1996). In Louisiana, nutria (*Myocastor coypus*) have long been detrimental to baldcypress planting efforts (Blair and Langlinais 1960, Conner 1988, Hesse and others 1996). The use of plastic (Allen 1995, McLeod and others 1996) and PVC (Myers and others 1995) treeshelters has proved beneficial in preventing beaver and nutria from clipping seedlings.

First year height growth [average = 19.8 ± 1 centimeters (±1 SE)] of 1995-planted baldcypress was significantly less than second-year height growth (average = 50.8 ± 2.0 centimeters; fig. 1). First-year height growth of the 1996-planted baldcypress was 44.0 ± 1.6 centimeters (fig. 2). There may be many explanations for the lower first-year height growth of the 1995-planted seedlings. However, most plants that have developed under drained conditions (nursery-grown) experience some degree of root dieback upon flooding, regardless of their ability to tolerate flooded conditions (Hook and Brown 1973, Sena Gomes and Kozlowski 1980, Syvertsen and others 1983, Topa and McLeod 1986). Lateral roots may either die back to the tap root or to the primary lateral from which they originated, and thick, succulent, relatively unbranched roots (soil water roots) may be initiated from the point of dieback in root systems undergoing acclimation to flooding (Hook and others 1970). By pruning the root systems of the 1996-planted seedlings, the die back phase was eliminated and new roots developed immediately as was been shown by Conner (1995).

First-year height growth of 1996-planted water tupelo averaged 25.0 ± 3.0 centimeters, and there was a significant difference between the two areas planted. In one area, water tupelo height growth was 18.7 ± 3.1 centimeters compared to 31.9 ± 4.8 centimeters in the other area (fig. 2). This difference is probably due to the difference in the amount of competition in the two areas. One area was densely populated with cattail, and was so thick it was difficult to find the seedlings even with the PVC stakes.

CONCLUSIONS

Today, there are numerous opportunities to reestablish forested wetlands on disturbed sites. Root-pruned seedlings allow for the quick and easy insertion of seedlings into flooded sediments. Early growth and survival are adequate to reestablish forests as long as beaver does not become too much of a problem. Treeshelters may be one way to prevent herbivory problems with newly planted seedlings. The impacts of root pruning on long-term survival and growth are unknown and require further study.

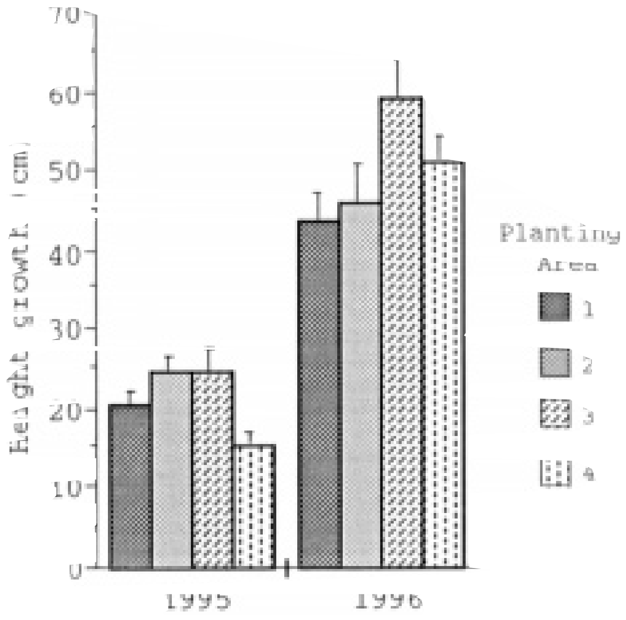

Figure 1—Height growth (cm) of baldcypress seedlings planted in 1995 in four areas of the Pocotaligo Swamp.

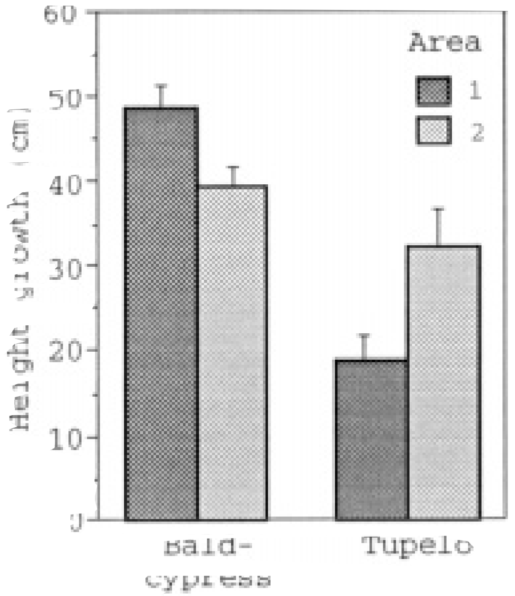

Figure 2—Height growth (cm) of baldcypress and water tupelo seedlings planted in 1996 in two areas of the Pocotaligo Swamp.

ACKNOWLEDGMENT

Funding for the plantings was provided by the Pocotaligo Swamp Restoration Committee. The field assistance of AMERICORPS in 1996 is gratefully acknowledged. Belle W. Baruch Forest Science Institute Technical Contribution: 97-01.

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WATER RELATIONS AND MORPHOLOGY OF NUTTALL OAK SEEDLING SPROUTS

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Abstract—Seedling sprouts are considered the most reliable source of oak regeneration in bottomland hardwood forests. This is because rapid shoot growth encouraged by a high root/shoot ratio provides oak seedling sprouts a competitive opportunity in regenerating stands. To learn more about the physiological mechanisms supporting this rapid shoot growth, a greenhouse study was designed to determine whether altered water transport rates facilitated the rapid shoot growth of Nuttall oak (*Quercus nuttallii* Palmer) seedling sprouts. In February 1996, sixty 1-0 seedlings were established in 15-liter pots containing a potting soil mix. Shoots were clipped on half of the seedlings about 5 centimeters above the root collar to promote sprout development. Measurements of stem growth, biomass accumulation, leaf physiology and sap flow indicated that physiological functions of Nuttall oak seedling sprouts were probably moderated after a balance was restored between root system size and shoot size of the sprout.

INTRODUCTION

Seedling sprouts, a form of coppice reproduction, develop from dormant buds above the root collar following damage or dieback of the terminal shoot (Johnson 1993, Kramer and Kozlowski 1979). Under repetitive shoot dieback and resprouting, the seedling sprout develops a high root:shoot ratio which can facilitate a quick growth response when released (Johnson 1993). Seedling sprouts are especially important to bottomland oak (*Quercus* spp.) species, because oaks typically follow a regeneration strategy that relies on accumulating advance reproduction in a regeneration pool (Johnson 1993). A regeneration pool well-stocked with advance oak reproduction is required to ensure successful oak replacement after stand disturbance.

Since sprouts serve as an important source of oak regeneration, some research has focused on revealing the physiological mechanisms underlying the rapid shoot growth observed for this form of reproduction (Lockhart and Hodges 1994, Kruger and Reich 1993a, 1993b). However, except for leaf-level aspects, few studies have examined the influence of the high root:shoot ratio of a seedling sprout on its water relations (Blake and Tschaplinski 1986, Kruger and Reich 1993b, Syvertsen 1994). This study was designed to determine whether altered water transport rates facilitate the rapid shoot growth of seedling sprouts. To determine this, a greenhouse study was designed with the objectives of: (1) quantifying shoot growth, (2) quantifying sprout morphology in terms of biomass accumulation, and (3) describing the sap flow patterns of oak seedling sprouts.

METHODS

Experimental Material

Sixty 1-0 Nuttall oak (*Q. nuttallii* Palmer) seedlings were potted in 15-liter polyethylene pots with a 50:50 (volume:volume) sphagnum peat and sand mixture (pH = 4.2). Pots were placed in a greenhouse and given a single application of 20-20-20 Osmocote (Grace Sierra, Milpitas, CA 95035) time release fertilizer. Soil was watered as needed to maintain field capacity in all pots during the entire growing season. To promote sprout development, 30 randomly selected seedlings were shoot-clipped with pruning shears about 5 centimeters above the root collar. Plants were grown under ambient light in the greenhouse for about 9 months between February and October 1996.

Measurements

To quantify sap flow of the experimental plants, four randomly selected seedlings and sprouts were fitted with Dynagage SGA10-WS stem-flow gauges and monitored with a Flow32 Sap-flow Datalogger System (Dynamax, Incorporated, Houston, TX 77099). The Dynamax sap-flow system uses an energy balance method to estimate velocity of sap flow from known inputs of continuous heat supplied to the stem flow gauge. Sap flow was monitored on the eight plants for a 3-week period in September. These measurements were planned for earlier in the growing season, but the stem flow gauges used in this study required a minimum shoot diameter of 10 millimeters, and experimental material did not attain this size until late in the growing season. While sap flow measurements were in progress, air temperature, relative humidity, and photosynthetically active radiation were monitored in the greenhouse with a LI-COR LI-1000 data recorder and appropriate sensors.

During the 3-week sample period, three cloud-free days were selected as sample days to quantify leaf physiology of the experimental plants. On each of these three days, measurements of net photosynthesis and transpiration were made on eight randomly selected seedlings and sprouts. Net photosynthesis was measured with an ADC LCA3 Portable Photosynthesis System (Analytical Development Company Limited, Hoddesdon, England), while stomatal conductance and transpiration rate were measured on these same plants with a LI-COR, LI-1600 Steady State Porometer (LI-COR, Incorporated, Lincoln, NE 68504). All gas exchange measurements were performed on leaves from the terminal flush of selected plants between 1000 and 1100 hours solar time.

Height and root-collar diameter were measured on all seedlings before clipping and after the 9-month growing period. Following 9 months of growth, all 60 plants were

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harvested and separated into root, stem, and leaf biomass. All biomass components were oven dried at 50 ^{o}C for 7 days before measuring dry weights to the nearest 0.01 gram with an analytical balance. Root:stem ratios were computed by dividing root biomass with stem biomass for each plant.

Statistical Analyses

Analysis of variance for a completely random design was used to test for a treatment effect on plant height, root-collar diameter, biomass accumulation, and root:stem ratio. Leaf physiology variables were also analyzed according to a completely random design, but sample day (replication) served as a source of variation in the model. A similar model was used to analyze treatment effects on sap flow. Analysis of variance was performed on the daily accumulation of sap flow of gauged plants on three cloud-free days during the 3-week sample period. All statistical tests were conducted at the 0.05 probability level.

RESULTS AND DISCUSSION

Seedling Growth

Before shoot clipping, seedlings of both treatments were about 39 centimeters tall with a root-collar diameter greater than 5 millimeters (table 1). All clipped seedlings resprouted from dormant buds above the root collar, and no seedling mortality was observed during the experimental period. After the 9-month experimental period, shoot clipping did not significantly affect height or root-collar diameter of plants (table 1). Thus, if relative growth is considered, it is obvious that sprout shoots grew considerably more than seedlings. The height increment of seedlings was 41 centimeters, while the height increment of sprouts was 86 centimeters. These height increments equate to 100 percent and 1700 percent relative growth rates, respectively.

Other investigations into the growth of oak seedling sprouts are in accord with these findings. For example, the height of white oak (*Q. alba* L.) seedlings was not influenced by shoot clipping for two of three half-sib families studied by Kormanik and others (1995). In another field study, Lockhart and others (1993) found relative height and diameter growth of cherrybark oak (*Q. pagoda* Raf.) natural regeneration was increased by shoot clipping, so that sprouts attained the same size as intact seedlings within 4 years after clipping. Similarly, Kruger and Reich (1993b) reported that a compensatory growth response by sprouts diminished any effect of shoot removal from northern red oak (*Q. rubra* L.) seedlings that were clipped while dormant. However, results from this study and others cited here indicate the increase in relative growth rate exhibited by shoot-clipped oak seedlings may not be maintained beyond the initial height of the seedling.

Biomass Accumulation

For both seedlings and sprouts, roots composed the largest component of plant biomass, and leaves contributed the least to total plant mass (table 2). There was no observable effect on plant morphology 9 months after shoot clipping, as differences in biomass accumulation were not detected for any of the plant components (table 2). As a result, root:stem ratios for both seedlings and sprouts averaged about 2.9 ± 0.13 (mean ± standard error) ($P > F = 0.8954$) at the end of the experimental period. Root:stem ratio increased during the growing season from a pretreatment value of 1.4 ± 0.05.

The rapid growth often observed on sprout shoots of many tree species is often linked to an increased sink demand of the developing stem. If shoot removal completely eliminates the photosynthetic surface of oak seedlings, initial sprout development is supported by carbohydrate reserves translocated upward from the roots (Kruger and Reich 1993b). For natural regeneration of cherrybark oak, stored carbon reserves and current

Table 1—Initial and final height and diameter (mean ± SE) for Nuttall oak seedlings and seedling sprouts grown in a greenhouse for 9 months (n=30)

Measurement	Seedlings	Sprouts
Height (in centimeters)		
Initial[a]	38.8 ± 0.5 a	38.8 ± 0.7 a
Final[b]	79.5 ± 5.0 a	91.2 ± 6.2 a
Diameter (in millimeters)		
Initial[c]	5.4 ± 0.2 a	5.8 ± 0.2 a
Final[d]	11.4 ± 0.2 a	11.8 ± 0.4 a

[a] Treatment means followed by the same letter in a row are not different. $P > F = 0.9693$.
[b] $P > F = 0.1478$
[c] $P > F = 0.2004$
[d] $P > F = 0.4010$

Table 2—Biomass accumulation (mean ± SE) by plant component for Nuttall oak seedlings and seedling sprouts grown in a greenhouse for 9 months (n=30)

Component	Seedlings	Sprouts
	- - - - - - - - - - - *Grams* - - - - - - - - - - - -	
Root[a]	74.1 ± 2.1 a	77.4 ± 2.6 a
Stem[b]	27.2 ± 1.6 a	29.9 ± 2.0 a
Leaf[c]	18.7 ± 1.2 a	21.8 ± 0.9 a
Total[d]	119.9 ± 3.8 a	129.1 ± 4.1 a

[a] Treatment means followed by the same letter in a row are not different. $P > F = 0.3199$.
[b] $P > F = 0.3079$
[c] $P > F = 0.0583$
[d] $P > F = 0.1099$

photosynthates produced by developing leaves were used to meet the demands of the developing shoot (Lockhart 1992). The lack of a treatment effect on the biomass distribution and total mass of plants in this study is particularly noteworthy. Apparently, sink demands of developing shoots were met and sprouts shifted into a carbon allocation pattern similar to that of intact seedlings at some point during the 9-month growing period. Root:stem ratios indicated that both seedlings and sprouts followed a carbon allocation pattern which favored biomass accumulation in roots. Northern red oak seedlings that received a dormant season shoot-clipping reportedly behaved in a similar manner (Kruger and Reich 1993b).

Leaf Physiology

Several existing studies have documented that increased rates of photosynthesis, stomatal conductance, and transpiration support the sink demands of the developing sprout shoot (Kruger and Reich 1993a, Tschaplinski and Blake 1989a, 1989b). It is argued that the high sink demand of the developing sprout shoot maintains the increased photosynthetic rate of leaves by reducing assimilate accumulation which may serve as a feedback mechanism limiting photosynthesis (Tschaplinski and Blake 1989b). Contrary to these published studies, the sampled Nuttall oak sprout leaves did not show elevated rates of photosynthesis, stomatal conductance, or transpiration (table 3). However, it is probable that enhancement of leaf physiology would have occurred while sprout shoots were in a stage of vegetative growth. Unfortunately, seedlings and sprouts had entered into a lag phase of shoot development prior to sampling for leaf physiology variables.

Table 3—Leaf physiology and sap flow (mean ± SE) for Nuttall oak seedlings and seedling sprouts grown in a greenhouse for 9 months

Process measured	Seedlings	Sprouts
Photosynthesis[a] (μmol m^{-2} s^{-1})	12.47 ± 0.7 a	11.9 ± 0.6 a
Stomatal[b] conductance (cm s^{-1})	0.80 ± 0.06 a	0.88 ± 0.05 a
Transpiration[c] (μg cm^{-2} s^{-1})	6.9 ± 0.4 a	7.4 ± 0.4 a
Sap flow[d] (grams per day^{-1})	439.2 ± 26.7 a	493.9 ± 24.9 a

n=8 with three replications for leaf physiology, n=4 with three replications for sap flow

[a] Treatment means followed by the same letter in a row are not different. P > F = 0.4828.

Sap Flow

Figure 1 presents sap flow of gauged seedlings and measured environmental variables in the greenhouse on a representative sample day. Similar diurnal patterns of water ascent were observed for seedlings and sprouts with peak flow rates of about 60 grams of water per hour occurring near solar noon (fig. 1). Analysis of the daily accumulated sap flow of gauged plants indicated that shoot clipping did not influence the sap ascent rate of sprouts near the end of the 9-month experimental period (table 3). Daily water transport through the stems of seedlings and sprouts was about four times the dry weight of the plant. Results were similar when sap flow rates were weighted by leaf area of individual sample plants (data not shown).

Few studies have examined the water relations of seedling sprouts. Blake and Tschaplinski (1986) proposed that the rapid growth of sprouts resulted from releasing the plant from water stress. They demonstrated that partial shoot removal improved water relations of poplar (*Populus deltoides* Bartr. X *Populus nigra* L. cv. DN22) seedlings within 5 days of clipping. Increased transpiration rates and water potential were attributed to an increase in the root:shoot ratio rendered by the clipping. Shoot-clipping may have temporarily improved water availability to sprouts

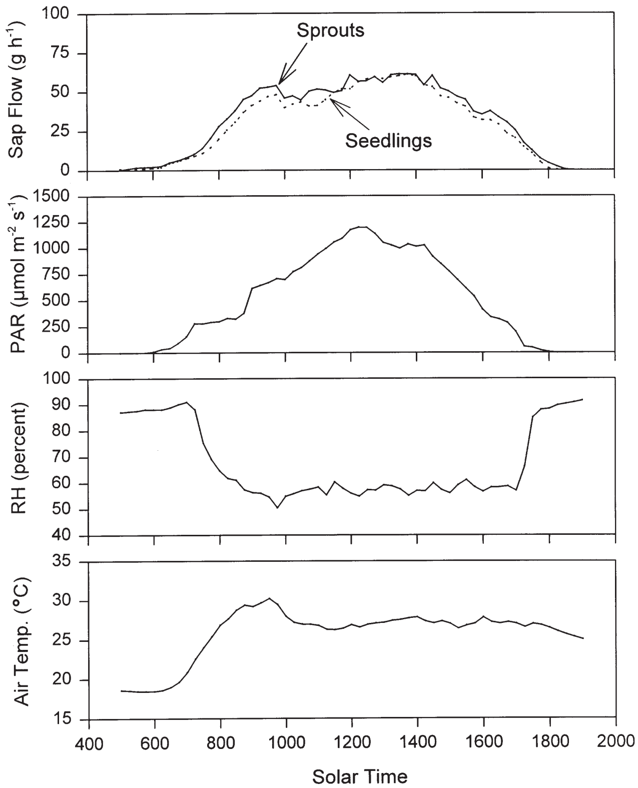

Figure 1—An example of the diurnal pattern of sap flow for Nuttall oak seedlings and seedling sprouts measured in a greenhouse on September 22, 1996. Sap flow lines represent the average of four plants for each reproduction type, and photosynthetically active radiation (PAR), relative humidity (RH), and air temperature in the greenhouse are presented for the sample day.

in this study, but this was not evident from sap flow measurements. Perhaps, sampling sprouts during a period of vegetative growth would have been more revealing.

CONCLUSIONS

Results from this study may be best explained in light of the growth pattern typically exhibited by oak seedlings. Oak seedlings exhibit relatively conservative semideterminant shoot growth patterns that are characterized by recurrent flushing (Dickson 1991). Bud expansion begins, leading to stem elongation, and leaf expansion follows stem elongation. Formation of a new bud occurs after leaves are fully expanded, and then the shoot enters into a lag phase or quiescent growth phase (Hanson and others 1986). During periods of vegetative shoot growth, leaf physiology is enhanced and assimilates are translocated upward in response to the sink strength of the developing shoot (Dickson 1991). In contrast, during the lag phase, photosynthesis is moderated and assimilates are translocated to the lower stem and roots (Dickson 1991). It is believed that this downward translocation of assimilates during the lag phase serves to restore starch reserves of the plant depleted during the flush episode (Dickson 1991). And, it serves to restore the water balance of the plant by contributing to root extension (Dickson 1991, Kruger and Reich 1993b). Thus, it appears that oak seedlings maintain a balance between the size of the root system and the size of the shoot (Kruger and Reich 1993a, 1993b).

In this study, it is assumed that shoot clipping created a root:shoot imbalance. From the literature, it may also be assumed that leaf physiology was enhanced to meet the demands of the sink strength of the sprout. Along with this, there may have been a shift in the water relations of the sprouts, possibly even sap flow rates. However, the root:shoot imbalance was corrected before sampling began. Prior to sampling, sprouts set bud and entered into a lag phase for the remainder of the experimental period. Once plants entered the lag phase, photosynthesis presumably was moderated. And, if water transport was increased during the development of the sprout shoots, it too was moderated upon shoot development. From this research, it appears that the physiological invigoration of sprouts often reported in the literature is not maintained by Nuttall oak regeneration once a balance between root system size and shoot size is restored.

However, it should be brought out that results reported for this greenhouse experiment may not be directly comparable to what occurs under field conditions with natural oak reproduction. In this study, both reproduction types were vigorous plant material that received ample water, sunlight, and an adequate nutrient supply. In the field, the relative difference between sprouts and seedlings may be greater in terms of morphology or anatomical characteristics such as vessel size. For example, suppressed seedlings may have a vascular system that is not able to support rapid movement of water to developing foliage. If vessel size is typically larger in sprouts than in seedlings, sprouts may have an advantage when responding to release. It would be beneficial to focus additional research in this area on reproduction growing in a natural environment.

ACKNOWLEDGMENT

The author is grateful to Dexter Bland, who installed and maintained the Dynamax sap flow instrumentation in the greenhouse. John Hodges, Ken Krauss, and Brian Lockhart provided critical reviews of an earlier draft of this manuscript.

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EFFECTS OF FLOODING REGIME, MYCORRHIZAL INOCULATION AND SEEDLING TREATMENT TYPE ON FIRST-YEAR SURVIVAL OF NUTTALL OAK (*Quercus nuttallii* PALMER)

Virginia Burkett and Hans Williams[1]

Abstract—Three different types of Nuttall oak (*Quercus nuttallii* Palmer) seedlings were planted on floodprone, former cropland in Mississippi, Louisiana, and Texas. The three types of 1+0 seedlings planted at each site in January and February of 1995 were bareroot seedlings, seedlings grown in 164 square centimeters plastic containers, and container-grown seedlings inoculated with vegetative mycelia of *Pisolithus tinctorious* (Pers.) Coker and Couch. Seedlings at the Mississippi site were planted in a split-plot design at three different elevations, which provided three different natural flooding treatments. Seedlings at the other two sites were planted in a Latin square design at a single elevation. Significant differences in the survival and condition of the seedlings during the first growing season were observed at the Louisiana site, favoring the inoculated container-grown seedlings over the other two stock types. First-year seedling survival at the site in Texas, which had the best drainage of the three sites, was not significantly different between treatments. Small mammals clipped 98 percent of the container-grown seedlings at the Mississippi site.

INTRODUCTION

Bottomland hardwood forested wetlands are characteristically exposed to soil saturation and periodic or continuous flooding at various times of the year. Depth to the permanent water table and timing, frequency, and duration of flooding play key roles in the occurrence and growth rate of hardwood species from seed germination, in early seedling survival, and in growth during establishment (Kennedy and Johnson 1984). Seedling survival can be strongly influenced by root morphology, which affects nutrient and water accumulation. Oak seedlings grown in containers develop more primary lateral roots and secondary roots than bareroot seedlings (Dixon and others 1981a).

The roots of forest seedlings are commonly ingrown with mycorrhizal fungi that penetrate the surrounding soil and provide access to a much greater soil volume than uninfected roots. The presence of mycorrhizal fungi may be especially important to seedling growth on harsher sites (Read 1991), because they enhance the transport of nutrients, water, and organic materials to the seedling. Dixon and others (1981a, b) found that leaf area, number of primary lateral roots, and carbohydrate reserves were increased in container-grown black oak seedlings that were inoculated with *Pisolithus tinctorious,* (Pers.) Coker and Couch, a common mycorrhizal fungus associated with many southern forest species.

Pisolithus tinctorius, an "ectomychorrizal" fungus which forms a mantle or sheath on the root surface, has been used effectively to enhance pine (*Pinus*) seedling growth and survival (Marx and others 1977). Mycorrhizal fungi are obligate plant symbionts; flooding, cropping, and fallow have been shown to reduce their populations. Despite the assumption that wetland plants are non-mycotrophs, wetland species generally develop mycorrhizae when soils become relatively dry (Allen 1990). The influence of seasonal flooding and soil anoxia on mycorrhizal development and functions in hardwood forests is poorly understood.

The purpose of this study was to determine the relative importance of seedling type and mycorrhizal inoculation in the growth of Nuttall oak seedlings for wetland reforestation.

METHODS

Seedling Culture

Common nursery practices were used to cultivate the container and bareroot seedlings used in these experiments. Thirty pounds of Nuttall oak seed were obtained from a seed source in the Delta area of Mississippi in late April of 1994 and placed in cold storage at 1.7 °C. The acorns were soaked overnight in a 5-gallon bucket of tap water; 111 acorns that floated were discarded. The remainder were placed in 18 plastic bags and refrigerated at 1.7 °C. Bags were turned and opened to check for spoilage three times each week through May 26, 1994, when 2,222 acorns were individually sown in 164-centimeter^3 plastic seedling cones (Ray Leach "Cone-tainer" Nursery, Canby, Oregon).

A 1:1 homogeneous mixture of autoclaved peat moss and construction-grade vermiculite was used as a planting medium for the container stock. A total of 2,222 seeds were sown, thoroughly watered, and placed in a greenhouse at Stephen F. Austin State University. By July 18, a total of 1928 container seedlings had been produced and moved into an outdoor shadehouse. They were fertilized biweekly and watered as needed.

On July 6, 1994, every other tray of seedlings in the shadehouse was removed and inoculated with vegetative mycelial inoculum of *P. tinctorius.* One-half (5 grams of

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fungal mycelia) of a commercially available inoculum kit was applied in a drench following procedures recommended by the distributor (Mycorr Tech, Inc., Pittsburgh, PA). Seedlings were inoculated again on August 30 and December 21, 1994. The inoculated seedlings were maintained on separate tables in the shadehouse but otherwise treated the same as the noninoculated stock.

Bareroot seedlings (46 centimeters or larger) were obtained from the same seed source and seed lot as the container-grown seed.

Morphological Analysis Prior to Planting

On January 5, 1995, 50 seedlings of each container seedling type (container with inoculation and container without inoculation) were selected using a random numbers table. They were gently removed from their containers and soaked in tap water for 1 hour to loosen the potting medium. After washing, the exposed root systems were submerged in tap water overnight so that they would not dry out.

For the preplanting comparison of bareroot Nuttall oak seedlings with those grown in containers, 250 bareroot seedlings were obtained from the seed/seedling source in Mississippi. They were lifted from the nursery bed on January 3, 1995, and transported overnight in sealed shipping bags to Stephen F. Austin State University, where they were placed in cold storage at 1.7 °C. On January 6, 1995, 50 bareroot seedlings and the container seedlings that were harvested the prior day were brought into the laboratory for morphological and biomass measurements. Weight of aboveground and belowground plant material was measured using a Mettler PC 8000 analytical balance (Mettler Instrument Corp., Heightstown, NJ). Root volume was measured using a displacement procedure described by Burdett (1979). Stems and roots were placed in a drying oven at 60 °C. When a constant weight was reached, the dry weights of stem and root tissue were recorded.

For all statistical analyses used in these experiments the level of significance was established at $\alpha = 0.05$. A one-way analysis of variance (ANOVA; using Proc GLM of the Statistical Analysis System, SAS Institute Inc. Cary, NC) was used to test for fixed treatment effects on seedling morphology prior to planting. If significant differences were found between at least two of the three seedling types, means were compared using Duncan's multiple range test (Freund and Wilson, 1993).

Field Trials

Yazoo National Wildlife Refuge, MS—Field experiments that involved the testing of seedling treatment and flooding regime were conducted at Yazoo National Wildlife Refuge (NWR) in the Delta Region of west-central Mississippi. The planting site was located on a tract of farmed wetlands that was recently annexed to the Yazoo NWR in Sharkey County, MS, 2.5 kilometers east of the community of Anguilla. A 1994 soil survey of the tract indicated that the soil type at this site is Sharkey clay (very fine, montmorillonitic, nonacid, thermic Vertic Haplaquept). The Sharkey soil contains montmorillonitic clay that, when dry, develops cracks that are from 2 to 10 centimeters wide and several centimeters deeper than wide (Soil Conservation Service 1962).

The field is roughly rectangular in shape, with a manmade drainage ditch running the entire length of the east side, from north to south along its long axis. The field has a very gentle slope (< 2 percent) dipping to the east, toward the drainage ditch. An RDS WL-80 water level recorder (Remote Data Systems, Inc., Wilmington, NC) was placed near the study plots on a wooden pile on the west side of the drainage ditch.

An elevation survey of the field was conducted to identify three elevation contours that would best represent three natural flooding regimes (i.e., whole plots): frequently flooded, less frequently flooded, and not flooded. The three elevations relative to mean sea level are 28.1 meters, 28.8 meters, and 29.4 meters. Four 22.8-meter by 7.6-meter whole plots (i.e., replications) were laid out lengthwise along each of the three elevations, with a 7.6-meter spacing between each plot. Each whole plot was subdivided into three 7.6-meter by 7.6-meter subplots, oriented parallel to the elevation gradient. Each of the three seedling treatments was assigned at random to one of the subplots or "split plot" within each whole plot.

Container seedlings were transported in a covered van from the university to the site on January 9, 1995. Bareroot seedlings were lifted from the nursery bed on January 9 and transported in sealed shipping bags directly to the planting site at Yazoo NWR on January 10, 1995. Thirty seedlings were planted with a planting shovel on January 10 and 11, 1995, in each subplot on a 1.5-meter by 1.5-meter spacing arrangement.

Plant competition at each of the three elevations on August 19, 1995, was compared by describing the percentage cover by species and overall height in a 1-square meter plot located between each whole plot at each elevation.

Alazan Bayou Wildlife Management Area, TX—The Alazan Bayou Wildlife Management Area (WMA), owned and managed by the Texas Parks and Wildlife Department (TP&W), is located in northeastern Texas, approximately 10 miles north of Lufkin in Nacogdoches County. The WMA includes approximately 800 hectares of former pasture and bottomland hardwood forests, mostly located along Alazan Bayou. A relatively low and flat mowed area on the southern end of the tract was selected for the field trials at Alazan Bayou WMA. The 1980 soil survey of Nacogdoches County indicates that the site is Mantachie sandy loam (fine loamy, silicious, acid thermic Aeric Fluvaquent; Dolezel and Fuchs 1980).

There was only one main factor of interest at the Alazan Bayou site: seedling treatment at three fixed qualitative levels (bareroot, container, and container with inoculation). Three 22.8-meter by 7.6-meter blocks (i.e., reps), numbered 1, 2, and 3, were laid out in a north-to-south direction. Each of the blocks was split into three equal size plots (7.6 meters by 7.6 meters), oriented in an east-to-west direction. For Block 1, each of the seedling treatments was randomly assigned to the plots. The seedling treatment assigned to the westernmost plot of Block 1 was then assigned to the middle plot of Block 2; the seedling treatment assigned to the middle plot of Block 1 was assigned to the easternmost plot of Block 2; and so forth, creating a 3 by 3 Latin Square design. The order of experimentation was restricted, that is, blocked in two directions: rows and columns.

Ninety bareroot seedlings were selected at random from those that had been placed in cold storage at the university on January 4, 1995. Ninety container seedlings of each treatment type were selected at random from those that remained in the shadehouse. Seedlings were planted with planting shovels in rows in each plot on a 1.5-meter by 1.5-meter spacing arrangement on February 9, 1995.

To compare the morphology of seedlings at the end of the first growing season, three randomly selected seedlings were dug up from each of the nine plots with a planting shovel on January 30, 1996. The procedures that were used to measure all variables but root area were the same as those used in the preplanting analysis of seedlings. For root area measurements, lateral roots were removed with a small scalpel and scanned with the Li-Cor Portable Area Meter (LI-3000 A, Lincoln, NE).

Bayou Macon Wildlife Management Area, LA—Bayou Macon WMA in northeast Louisiana, owned and managed by the Louisiana Department of Wildlife and Fisheries, is located east of Bayou Macon between State Highways 2 and 582, approximately 15 kilometers west of the Mississippi River. The predominant cover type is bottomland hardwood forest, but 644 hectares had been clearcut and used for agricultural purposes before the land was purchased by the State. The soil type at the Bayou Macon WMA planting site is Sharkey clay[2] (Allen and others 1988).

The experimental design at the Bayou Macon WMA was the same as that used at the Alazan Bayou site in Texas. Seedling treatment was the only factor of interest. Seedlings were planted with planting shovels on December 14, 1995.

Data analyses—Analysis of variance (using Proc GLM, SAS) was used to test for treatment effects on seedling height and other continuous response variables measured in-situ at each site. The responses were transformed, if necessary, to meet the assumptions of homogeneity for the error terms of the model. If significant differences were found between treatments, means that involved two populations (e.g., flooded and nonflooded plots) were compared using the least significant difference or LSD test (Fisher 1960). Duncan's multiple range test was used to compare means from three different populations (e.g., three different seedling types).

For the analysis of the morphology of the 1+1 seedlings harvested at Alazan Bayou WMA, a multivariate analysis of variance (MANOVA, SAS) was performed on those responses which appeared correlated; otherwise, a univariate analysis was performed. Prior to MANOVA, each variable was tested for homogeneous variance assumptions and normality. Means were compared using Duncan's multiple range test when significant differences were found.

Categorical data analyses (using Proc Catmod, SAS) were used to compare rates of survival, dieback, herbivory, and basal sprouting among seedling treatments and flooding regime. If normality assumptions were not met by the categorical model, a binomial test of proportions was used to test for differences between treatments. Contrasts were used to compare means where significant differences were found.

RESULTS

Morphological Differences Prior to Planting

All morphological measurements indicated significant differences between the 1+0 bareroot and the container seedlings prior to planting (table 1). The bareroot seedlings had a significantly larger stem biomass and root collar diameter than the inoculated and noninoculated container seedlings. The initial height of the average bareroot seedling was approximately 10 percent higher than that of the container seedlings. The root systems of the bareroot seedlings were also significantly larger than those of the container seedlings, but the container seedlings had roughly twice as many primary lateral roots. The only significant morphological difference found between the two container seedling treatments prior to planting was the number of primary lateral roots greater than 0.5 millimeters. The inoculated container seedlings had 17 percent more primary lateral roots than the container seedlings that were not inoculated (table 1).

Table 1—Morphology of the three types of Nuttall oak seedlings prior to planting at the three field sites (means within a row having a common superscript are not significantly different, $\alpha = 0.05$)

Inoculated variable	Bareroot	Container	Container
Stem height (cm)	70.4^a	60.3^b	65.6^b
Stem dry weight (g)	12.95^a	4.52^b	4.65^b
Root dry weight (g)	11.30^a	7.51^b	7.41^b
Stem diameter at root collar (mm)	13.0^a	9.0^b	9.0^b
Root volume (ml)	11.55^a	3.50^b	3.71^b
Primary lateral roots	16^c	30^b	35^a

[2] Personal communication. June 17, 1996. Floyd Hooker, NRCS, Lake Providence, LA.

Yazoo National Wildlife Refuge

The planting site at Yazoo NWR was partially flooded twice during the first growing season. The lowest elevation, 28.1 meters mean sea level, was flooded continuously from March 8 to March 23, 1995 and again from April 26 to May 1, 1995. This flooding exposed the seedlings at the lowest elevation to 21 days of flooding. The middle planting elevation was flooded for only five days (March 16 to 20) during the first flood event and seven days (April 24 to 30) during the second event. The highest planting elevation, 29.4 meters mean sea level, did not flood during either event.

The predominant plant species that naturally invaded the planting site at the lowest elevation was *Iva annua*, which covered an average 75 percent of three 1-square meter plots sampled on August 17, 1995. No other species had more than 5 percent cover at any elevation in the canopy of the competing vegetation at the lowest elevation. Competition in the middle plots was more diverse, with *Iva annua* and *Sorghum halepense* (Johnson grass) occupying 45 percent and 25 percent of the upper canopy, respectively. The upper plots were heavily dominated by a dense growth of Johnson grass, which covered an average of 90 percent of each meter quadrant sampled.

Early in the first growing season (June 1, 1995) average survival (aboveground) of both types of container-grown seedlings exceeded 96 percent at all three elevations. At that time, survival of the bareroot stock averaged 45 percent, 27 percent, and 31 percent at the highest, middle, and lowest elevations, respectively. Survival through the end of the first growing season was difficult to compare among treatments because only 18 of the 720 container-grown seedlings had not been clipped by rodents. The container seedlings at the higher elevation were the first to be clipped, probably because there was more protective cover for rodents under the dense growth of Johnson grass. *Iva annua*, which dominated the competition at the lower elevation, reached comparable height but has a canopy structure that allows much higher light penetration at ground level.

Alazan Bayou Wildlife Management Area, TX

The survival and development of basal sprouts in seedlings during the first growing season at Alazan Bayou was not significantly different among the three seedling treatments (table 2). The categorical data analysis did detect significant effects of seedling treatment on shoot dieback, which was generally confined to the upper 10 centimeters of the stem. One third of the bareroot seedlings experienced partial dieback, compared to an average 67 percent dieback in both types of container stock (table 2).

Live stem length was significantly higher in the container-grown seedlings, even though they were more prone to partial shoot dieback (table 3). Root biomass and stem diameter were significantly higher in the bareroot seedlings. The inoculated container seedlings had a significantly higher number of first-order lateral roots than did the other seedling types, but there were no significant differences in the area of the primary lateral roots in the three types of seedlings. The total volume of taproot and lateral roots in the bareroot seedlings was greater than that of either container seedling type (table 3).

Table 2—Percentage of seedlings that survived, exhibited basal sprouts, and partially died back at the Alazan Bayou WMA in NE Texas during the first growing season (means within a row having common superscript are not significantly different, $\alpha = 0.05$)

Variables	Bareroot	Container	Inoculated container
Survival	94.08[a]	97.31[a]	97.31[a]
Basal sprout	5.91[a]	1.61[a]	2.80[a]
Partial dieback	33.33[b]	66.66[a]	68.18[a]

Table 3—Morphology and biomass of seedlings after first growing season at Alazan Bayou WMA in NE Texas (means within a row having same superscript are not significantly different, $\alpha = 0.05$)

Variables	Bareroot	Container	Inoculated container
Stem length (cm)	57.1[b]	71.7[a]	66.1[a,b]
Stem biomass (g)	3.38[a]	2.92[a]	2.94[a]
Root biomass (g)	4.12[a]	2.63[b]	2.53[b]
Stem diameter (mm)	11.0[a]	10.2[b]	9.8[b]
Root volume (ml)	6.2[a]	4.5[b]	4.6[b]
Lateral root area (cm^2)	9.17[a]	9.17[a]	9.04[a]
Tap root length (cm)	17.2[b]	21.4[a]	18.3[b]
Primary lateral roots (#)	33[b]	39[a,b]	46[a]

Bayou Macon Wildlife Management Area, LA

Seedling height, the only continuous variable measured at the end of the first growing season at Bayou Macon WMA, was significantly different among all three seedling treatments. The inoculated container seedlings were 20 percent and 79 percent taller than the noninoculated container and bareroot stock, respectively (table 4). The categorical data analyses did not detect any significant differences in basal sprouting or dieback among seedling treatments. Both types of container seedlings experienced greater herbivory by deer than the bareroot seedlings, but the differences were significant only between the bareroot and non-inoculated container seedlings (table 4). Survival among the inoculated container seedlings was 97 percent, which was significantly higher than that of the noninoculated container and bareroot stock (i.e., 88 percent and 79 percent, respectively) (table 4).

Table 4—Comparison of mean first-year height and survival among seedlings planted at Bayou Macon WMA in NE Louisiana (means within a row with same superscript are not significantly different, $\alpha = 0.05$)

	Variable		
Seedling treatment	Height	Survival rate	Deer browse
	Cm	- - - - - *Percent* - - - - -	
Bareroot	32.8^{c}	78.8^{b}	3.4^{b}
Container	48.8^{b}	87.5^{b}	15.6^{b}
Inoculated container	58.7^{a}	96.6^{a}	$7.3^{a,b}$

DISCUSSION

Morphological differences between the 1+0 bareroot and container-grown seedlings were significant and can be used, in part, to explain the differences in the survival and condition of the seedlings during the first growing season after planting. The root systems of the bareroot stock consisted primarily of a large taproot with roughly half as many primary lateral roots as the container-grown seedlings. This lack of root surface area has implications for reduced water and nutrient uptake, which may have offset the growth potential advantages associated with the larger biomass and height of the bareroot seedlings.

Differences in first-year survival among the three seedling types at Yazoo NWR were difficult to evaluate because most of the container seedlings were clipped at or near the root collar by rodents. Few container-grown seedlings sprouted after they were clipped in mid-August. However, both the bareroot and container-grown seedlings may resprout during the second growing season.

Morphological differences between seedling types diminished greatly after the first growing season at Alazan Bayou WMA, which had the most efficient natural drainage of the three sites. In addition, height growth among seedlings had shifted, favoring the container stock, even though partial dieback was more prevalent among the container stock. There was no significant difference in survival among the seedling types at this site. However, the noninoculated container seedlings grew significantly taller than the bareroot seedlings, despite the greater rate of partial dieback. The high rate of partial dieback among both types of container-grown seedlings could be related to one or more of the following factors: a higher demand for water associated with their more highly developed root systems, increased vulnerability of their more slender stems to damage by ice and freezing temperatures, and, possibly, the indirect effects of biweekly fertilization.

After the first growing season, the number of lateral roots in the bareroot stock was no longer significantly lower than that of the noninoculated container stock, but the number of lateral roots in the inoculated container seedlings was significantly higher than the other two seedling types. The noninoculated container seedlings grew significantly taller than the bareroot stock, but both types of container seedlings were twice as prone to dieback as the bareroot stock.

At Bayou Macon WMA, the drainage of local precipitation from the field was very slow, but it was not inundated by backwater flooding. The significance of the improved survival among the inoculated container stock at Bayou Macon WMA is possibly related to the more highly developed root system of these seedlings, which was induced by confinement in containers, frequent watering and fertilization, and more extensive mycorrhizal development.

CONCLUSIONS

Seedling culture clearly influenced the morphology of the root systems in the three types of seedlings used in these experiments. The highly fibrous root system of the container-grown seedlings may present potential advantages when planted at sites that are prone to drought and/or flooding. Inoculation of the container seedlings with vegetative mycelia of *P. tinctorious* slightly, but significantly, enhanced root fibrosity.

During the first growing season at Alazan Bayou WMA, the morphological differences between seedling types diminished. At this site, which had the most efficient drainage of the three planting sites, there were no significant differences in seedling survival among the three seedling types. The container-grown seedlings were twice as prone to dieback as the bareroot seedlings; however, their overall height growth was greater. Height growth was also greater among the container-grown seedlings at the Louisiana site. At Bayou Macon WMA, where drainage was poor but there was no long-term inundation, significant improvements in first-year survival and growth among the inoculated container stock could be attributed to seedling culture and related differences in root morphology. At Yazoo NWR, loss of stem tissue in 98 percent of the container-grown seedlings to small mammals precluded a meaningful comparison of first-year survival among the three treatments.

Seedling sprouting and survival during the second and third growing seasons should provide further insight into the relative importance of seedling type. The first year after planting, however, appears to be a very critical period in which seedling morphology, flooding, and herbivory have significant impacts on growth and survival, especially on sites that are prone to flooding.

ACKNOWLEDGMENT

The authors wish to sincerely thank the staff of the State and Federal refuges mentioned herein, and John McCoy, Darren Johnson, Parker Day, Julie Bennet, Hallie Loetz, and Andrew Couch for their invaluable assistance.

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INFLUENCE OF HYDROLOGY ON ARTIFICIAL REGENERATION OF OAKS IN THE MISSISSIPPI DELTA

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Abstract—Artificial hardwood regeneration on hydric agricultural sites, commonly known as farmed wetlands, has had little success in the Lower Mississippi Alluvial Valley, which consists of Mississippi, Arkansas, and Louisiana. A commonly held belief is that the failures are often the result of flooding events which occur on these sites. The objective of this study was to determine the influence of hydrology on the establishment and growth of two species of oak seedlings in four different, artificially controlled, flooding regimes planted at two dates on a farmed wetland site. Nuttall oak (*Quercus nuttallii*, Palmer) planted in December had the highest survival rate and leaf area measurements with regard to all flooding regimes, while willow oak (*Q. phellos*, L.) planted in March had the lowest survival rate, leaf area, and height growth in all flooding regimes.

INTRODUCTION

Of an estimated 24 million acres of bottomland hardwood forest present at the time of European colonization in the Lower Mississippi Alluvial Valley, commonly referred to as the Mississippi Delta, only 7.9 million acres of nonfederal forested wetlands remained as of 1993 (Cubbage and Flather 1993). These forested wetlands were cleared because of the higher value placed on agricultural products, and flood control structures were put in place to protect the agricultural crops.

Many of the forested wetlands that were cleared for agricultural production were not suitable for row crops because of backwater flooding characteristic to this area. Backwater flooding occurs when the water level of the Mississippi River rises higher than the water levels of streams and rivers inland. When this occurs, flood control structures prevent the inland waterways from flowing into the Mississippi River and many sites in the Delta are flooded. As a result, Federal, State, and private land managers have expressed interest in reforesting these farmed wetland areas rather than continuing to take annual economic losses from row crop destruction.

Bottomland hardwood forests are important economically for their timber production and hunting and fishing revenues. They also provide necessary ecological functions and supply noncommodity values (Wharton and others 1982, Wilkinson and others 1987). Some of the ecological functions of wetlands are nutrient cycling, biogeochemical cycling, and hydrologic cycling (Walbridge 1993).

Under the legislation of the Federal Agriculture Improvement and Reform Act of 1996, specifically the Wetlands Reserve Program, lands that are classified as farmed wetlands may be reforested through the help of the Federal Government by different economic programs (Federal Agriculture Improvement and Reform Act 1996). As a result of this support, many flood-prone sites in agricultural production have been and will continue to be reforested. Two methods of artificial regeneration are commonly used in the South. They are direct seeding and seedling planting (Johnson 1989, Johnson and Krinard 1985). Both are used on sites where no oak component exists.

On these open agricultural fields, light is not the limiting factor at time of planting of oak seedlings (Hodges and Gardiner 1992). Depending on when it occurs and the duration, flooding can influence the performance of oak seedlings (King 1995, Kozlowski and Pallardy 1979, Malecki and others 1983, Pezeshki and Chambers 1985, Streng and others 1989). Physiological functions such as stomatal conductance and photosynthesis are altered by flooding conditions and can affect the growth of oak seedlings. Kozlowski and Pallardy (1979) determined that flooding induced stomatal closure for *Fraxinus pennsylvanica* (green ash), which reduced the rate of photosynthesis. Pezeshki and Chambers (1985) found that stomatal conductance and net photosynthesis of *Quercus pagoda* (cherrybark oak) seedlings were significantly lower in flooding periods compared to preflooding conditions, indicating that this species encountered stress caused by flooding. Physiological conditions as affected by hydrology may lead to seedling stress that can hinder growth responses and survival (Pezeshki and Chambers 1985).

This study was designed to provide information on techniques for artificial regeneration of oaks on these types of hydric agricultural sites.

METHODS

Study Site

The study area is in the Lower Mississippi Alluvial Valley, more specifically in Sharkey County, MS, on the U. S. Fish and Wildlife Service, Yazoo National Wildlife Refuge. The area is known as the Sharkey Research Site. It was chosen because it was in agricultural production of soybeans and cotton prior to the installation of the research project, and it contained the characteristics of a farmed wetland.

The site is usually inundated during the dormant season (December - March), but it also floods for frequent periods during the early part of the growing season (April and

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May). This was an important characteristic in choosing the site for this research because many of the farmed wetlands in the valley are subject to flooding during the early part of the growing season. The growing season for this site occurs from February to October (Soil Conservation Service - USDA 1991).

The soil type is Sharkey clay (very fine, montmorillonitic, nonacid, thermic, Vertic Haplaquepts) (Soil Conservation Service - USDA 1975). It is currently classified as a hydric soil (Soil Conservation Service - USDA 1991). Because it is a montmorillonitic soil, the physical properties are altered by shrinking and swelling of the soil particles due to moisture level changes. These changes in the soil may prevent formation of traffic pans.

Study Objectives

The objectives of this research were to determine, for two oak species (Nuttall oak and willow oak); (1) the influence of hydroperiod on seedling establishment and development, and (2) the influence of planting date on seedling survival and growth.

Null Hypothesis

The general null hypothesis was that hydrologic conditions were not the controlling factor for successful regeneration of planted Nuttall and willow oak seedlings on these particular sites. Specific null hypotheses were as follows: (1) season of planting does not influence the success of the two species of planted red oak seedlings, and (2) flooding regimes do not have an effect on the performance of the two species of planted red oak.

Study Design

The study design was a randomized complete block design with split plots. Three levee impoundments, or replications, of 93 meters * 179 meters were constructed to hold water to mimic flooding. Water levels in the impoundments were controlled by pumps and a series of pipes and valves. This design permitted an evaluation of the effects of timing and duration of flooding on establishment of the red oak seedlings.

Within each impoundment, four flooding regimes were installed. They were as follows: (1) No-Flooding—control; (2) Winter/Spring flooding with no crown inundation—10 centimeters flood depth, January 20, 1996 to May 10, 1996; (3) Winter/Spring flooding with crown inundation—91 centimeters flood depth, January 20, 1996 to May 10, 1996, (4) Spring flooding with crown inundation after leafout—91 centimeters flood depth, May 10, 1996 to May 25, 1996.

Within each flooding regime, four treatments or experimental plots were installed. The treatments were Nuttall oak planted in December 1995, willow oak planted in December 1995, Nuttall oak planted in March 1996, and willow oak planted in March 1996. Each treatment plot size was 80 square meters. Each treatment consisted of 90 seedlings planted on a 0.6 meter * 0.6 meter scale. Seedlings for this study were purchased from a local vendor. This scale size was chosen because of the research area size limit. The close planting scale had no effect on seedling growth responses in the first 2 years of the study. All treatments were hand-planted in the same manner at both planting dates using hardwood planting shovels. This method of planting was chosen because the shovels had a broad head allowing for more space for the roots to expand. On this type of site, this method is used on an operational scale.

The response variables were seedling root/shoot ratios, seedling growth by height and groundline diameter, leaf area, and percent survival. Preseason height and diameter and root/shoot ratio measurements of seedlings were taken before dormancy broke for seedlings at both planting dates. Leaf area measurement dates were staggered throughout the 1996 growing season. First lateral, first flush, second lateral, second flush, third lateral, and third flush leaf area measurements were recorded when the seedlings were in their respective lag phase (Hanson and others 1986). Percent survival, root/shoot ratio, and height and diameter were recorded at the end of the growing season in November 1996.

RESULTS

Results are based on first-year, post-growing season data. Root/shoot ratios did not differ between flooding regimes (p=0.1648). Across all four flooding regimes (table 1), Nuttall December and Nuttall March seedlings had higher postseason root/shoot ratios (p=0.0377) than willow oak seedlings planted in March but not higher than willow oak planted in December (p=0.2994).

Height growth was significantly greater for No Flooding and Winter/Spring No Crown flooding vs. Winter/Spring Crown flooding and Spring flooding (p=0.0095). Nuttall December had significantly more height growth vs. the remaining three treatments (p=0.0007) (table 1). As shown in table 1, negative measurements were recorded for height growth due to stem dieback, which is common in oak seedlings. Diameter growth was greater for No-Flooding (p=0.0146) than Winter/Spring Crown flood, but there was no difference between Winter/Spring No Crown flood and Spring flooding (p=0.2739). Nuttall December and Nuttall March had significantly larger diameters (p=0.0103) than willow December and willow March (table 1).

Seedlings in the No Flooding regime had significantly higher leaf areas (p=0.0263) than seedlings in the remaining three flooding regimes, and the seedlings in the Winter/Spring No Crown flood had higher leaf area than those subjected to Spring flooding. Nuttall December was significantly higher (p=0.0001) than the remaining three treatments for leaf area. Willow December and willow March did not differ (table 1).

Percent survival was significantly higher (p=0.0104) for No Flooding, Winter/Spring Crown, and Winter/Spring No Crown compared to Spring flooding. For treatments, Nuttall December was significantly higher (p=0.0001) than the other three. Willow December and Nuttall March did not

Table 1—First-year average root/shoot ratio (R/S), height growth (HG), diameter growth (DG), leaf area(LA), and survival rate for Nuttall and willow oak seedling treatments for No Flooding, Winter/Spring No Crown flood, Winter/Spring Crown flood, and Spring flooding regimes (p=0.05)

Treatment	R/S	HG	DG	LA	Survival rate
		cm	*mm*	*cm²*	*Percent*
Nuttall December	1.9a	4.7a	1.3a	3,526.5a	82.6a
Willow December	1.5ab	-7.0b	0.4b	1,854.5c	68.9b
Nuttall March	1.7a	-4.0b	1.1a	2,705.8b	69.8b
Willow March	1.3b	-7.9b	0.3b	1,319.7c	33.1c

differ in survival rates. Willow March had the lowest survival rate (table 1).

DISCUSSION

In this study, Nuttall planted in December and March had the highest root/shoot ratios compared to the other treatments (table 1) and with all flooding regimes (tables 2 and 4). This species is typically found on lower sites which flood more frequently in the valley (Johnson 1975). Roots and shoots are interdependent throughout the life of a woody plant (Kozlowski 1971). Feedback between the root and shoot acts as a system of regulation for plant growth and development (Davies and Zhang 1991). There are three fundamental carbon allocation patterns in woody plants (Dickson 1991, Kozlowski 1992). They are determinate shoot growth, indeterminate shoot growth, and semideterminate shoot growth. Semideterminate shoot growth is common with *Quercus.* In this type of shoot growth, periodic flushes take place with intermediate lag stages (Hanson and others 1986). During the lag stages, reserves are stored in the roots. The results of this study indicate that more growth occurred in the Nuttall oak planted in December and March compared to the willow oak planted in December and March. Johnson (1975) found growth of Nuttall oak to be best on low sites where water stood into the early part of the growing season.

Height and diameter growth were both higher for No Flooding because the stresses of hydrology did not hinder the growth of both species of seedlings. According to Hook (1984), the shallower the water level, the less amount of stress the seedling has to overcome before it can grow.

Leaf area and survival were related in the measurements taken for this study. Higher leaf areas resulted in higher survival rates (table 1). These results indicated that Nuttall planted in December had higher leaf areas than Nuttall planted in March. This was one reason survival rates were significantly higher for Nuttall planted in December compared to the other treatments for all flooding regimes. Because these seedlings had more leaf area, more photosynthesis could be carried out, which increased

Table 2—First-year average root/shoot (R/S), height growth (HG), diameter growth (DG), leaf area (LA), and survival rate for Nuttall oak seedlings planted in December 1995 per flooding regime

Flooding regime	R/S	HG	DG	LA	Survival rate
		cm	*mm*	*cm²*	*Percent*
No Flooding	2.2	11.8	2.0	4,385.0	87.7
Winter/Spring No Crown flood	1.5	8.3	1.5	4,002.4	84.6
Winter/Spring Crown flood	2.1	-1.4	-0.1	2,951.5	78.5
Spring flooding	1.8	0.1	1.7	2,767.3	80.3

Table 3—First-year average root/shoot (R/S), height growth (HG), diameter growth (DG), leaf area (LA), and survival rate for willow oak seedlings planted in December 1995 per flooding regime

Flooding regime	R/S	HG	DG	LA	Survival rate
		cm	*mm*	*cm²*	*Percent*
No Flooding	1.8	-4.1	0.2	2,367.9	82.0
Winter/Spring No Crown flood	1.6	-2.2	0.2	1,736.1	71.3
Winter/Spring Crown flood	1.2	-11.7	0.6	2,024.2	72.5
Spring flooding	1.3	-10.1	0.6	1,289.8	49.6

Table 4—First-year average root/shoot (R/S), height growth (HG), diameter growth (DG), leaf area (LA), and survival rate for Nuttall oak seedlings planted in March 1996 per flooding regime

Flooding regime	R/S	HG	DG	LA	Survival rate
		cm	*mm*	*cm²*	*Percent*
No Flooding	1.9	1.9	1.5	3,870.8	74.8
Winter/Spring No Crown flood	1.3	-1.3	1.0	3,282.4	75.3
Winter/Spring Crown flood	1.8	-5.6	1.2	2,437.7	84.4
Spring flooding	1.9	-11.1	0.8	1,232.5	44.6

Table 5—First-year average root/shoot (R/S), height growth (HG), diameter growth (DG), leaf area (LA), and survival rate for willow oak seedlings planted in March 1996 per flooding regime

Flooding regime	R/S	HG	DG	LA	Survival rate
		cm	*mm*	*cm²*	*Percent*
No Flooding	1.1	-9.5	0.4	2,087.7	41.1
Winter/Spring No Crown flood	0.8	-2.9	0.5	631.6	31.4
Winter/Spring Crown flood	1.2	-12.5	-0.4	1,209.7	29.1
Spring flooding	2.0	-6.8	0.8	1,349.9	30.8

survival rates. Higher leaf area measurements existed in the No Flooding, Winter/Spring No Crown, and Winter/Spring Crown. The Spring flooding regime had the lowest ($p=0.0104$) survival rate with the lowest leaf area. The seedlings in the Spring flooding regime were damaged the most. According to Kozlowski and Pallardy (1997), flooding during the growing season is more damaging than dormant season flooding. The spring flooded seedlings were flooded after leafout occurred. The seedlings lost their leaves in the flooding event, therefore additional energy was required for the seedlings to start the process of initial shoot growth again after the water level was dropped. This may have caused the seedlings to use additional reserves in the roots. By doing this, they may not have had enough reserves in the roots to carry on root growth.

CONCLUSIONS

In this study, by analyzing the first-year results, we see that Nuttall oak seedlings planted in December withstood the stresses brought on by flooding very well with regard to survival, leaf area, and height growth in all flooding regimes (table 2). The No-Flooding regime, Winter/Spring No Crown flooding, and Winter/Spring Crown flooding had significantly higher rates of survival for both species at both planting dates compared to the Spring flooding regime. The Spring flooding proved to be most detrimental to the seedlings and, as shown in tables 2, 3, 4 and 5, willow oak seedlings did not perform as well as Nuttall oak seedlings for both planting dates in each flooding regime.

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FIRST-YEAR SURVIVAL AND GROWTH OF BAREROOT, CONTAINER, AND DIRECT-SEEDED NUTTALL OAK PLANTED ON FLOOD-PRONE AGRICULTURAL FIELDS

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Abstract—Container and 1-0 bareroot Nuttall oak (*Quercus nuttallii*, Palmer) seedlings were hand-planted, and acorns were direct- seeded, in a Sharkey soil (very fine, montmorillonitic, nonacid, thermic, Vertic Haplaquepts). The seedlings and seed were planted in January, February, March, and June, 1993. Flooding, to a depth of 2 meters, occurred on the study site from late March to late May. Seedlings planted in June were not flooded. Regardless of planting date, mean first-year survival for container seedlings was greater than 80 percent. Overall mean survival for bareroot seedlings was about 40 percent and direct-seeding survival was 30 percent. Bareroot seedling survival was about 60 percent when seedlings were planted in January or February, but fell below 25 percent when seedlings were planted in March and June. The reduction in bareroot survival was attributed to long-term cold storage. Mean first-year total height of container, bareroot, and direct-seeded seedlings was 46 centimeters, 34 centimeters, and 15 centimeters, respectively. However, stem dieback resulted in shorter seedlings after the first year in the field. Container seedlings were slightly shorter than when planted, but bareroot seedlings averaged 22 centimeters shorter. Greater survival and flexibility with regard to planting schedules may justify the use of container seedlings on flood-prone sites.

INTRODUCTION

Federal programs such as the Wetlands Reserve Program administered by the Natural Resource Conservation Service, and mitigation for wetland loss required by the U.S. Clean Water Act have initiated the increase in bottomland hardwood wetlands restoration in the Southeastern United States. Usually, the objective is to restore the wildlife and water quality wetland functions. Timber production, while enhancing the value of these reforested sites, is a secondary objective. Agricultural fields that flood in most years are ideal restoration sites because the presence of hydrology increases the opportunity for many wetland functions to occur. In addition, restoration costs may be reduced because little site preparation is needed prior to planting.

Flooding usually occurs in the Southeastern United States during the winter and early spring, which coincides with the conventional planting season. Consequently, this desirable flooding can cause significant problems during reforestation. Flood timing can disrupt seedling delivery and planting schedules, prolong cold storage of seedlings, or create difficult planting conditions. The long-term, complete inundation of newly planted flood-tolerant bottomland hardwood seedlings may reduce survival (Kozlowski and others 1991).

In 1991, the U.S. Army Corps of Engineers, Vicksburg District, began the reforestation of 3600 hectares of agricultural land located in Yazoo County, MS. The Lake George Wildlife/Wetland Restoration Project was initiated as mitigation for the Yazoo and Satartia Area Backwater Levee Project completed in 1987. The primary objective was to improve wetland and terrestrial wildlife habitat by planting a suite of mast-producing bottomland hardwood tree species. Reforestation was to be accomplished by using 1-0 bareroot seedlings. Except for some ponding, about 2650 hectares of the Lake George site is protected from flooding by an existing levee system. However, 405 hectares are unprotected and subject to backwater flooding from the Big Sunflower and Yazoo Rivers. Early survival of planted seedlings was high on areas that did not flood. However, survival was poor on sites where backwater flooding occurred after planting. Many of these areas had to be replanted, resulting in increased restoration costs and changes in the long-term planting schedule. The study objective was to observe the early survival and growth of seedlings planted on flood-prone sites on different dates and using different stocktypes.

METHODS

Container seedlings, 1-0 bareroot seedlings and acorns of Nuttall oak (*Quercus nuttallii*, Palmer) were hand-planted on January 22, February 16, March 18, and June 8, 1993. The seedlings were planted on a Sharkey soil series (very fine, montmorillonitic, nonacid, thermic, Vertic Haplaquepts) located at the Lake George site (U.S. Department of Agriculture 1975). The exact study location was chosen because the site was known to experience backwater flooding almost every year. The bareroot seedlings were purchased from a local forest tree nursery. All the bareroot seedlings used in the study were delivered in January and placed in cold storage at 5 ^{o}C until planting. The bareroot seedlings were packed in Kraft paper bag bundles of 100 to 250 seedlings. The roots were kept moist by a synthetic mulch.

The container seedlings were grown at facilities located at the U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. In May 1992, artificially stratified Nuttall oak seeds were sown into 164 cubic centimeter plastic cone containers filled with a 1:1 ratio of sphagnum peat moss and vermiculite. The acorns were purchased from a local seed vendor. Seed stratification was consistent with methods as described by Olson (1974). Container seedling density was 258 per square meter. Seedlings were

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established in the greenhouse; then, for the remainder of the growing season, they were placed in a shadehouse covered with a 50 percent shade cloth. Seedlings were watered daily and fertilized weekly with a complete fertilizer (20-20-20 or 15-45-15). Watering and mineral fertilization were reduced in September. Seedlings remained outside and in the containers until planted.

In fall 1992, Nuttall oak acorns for the direct-seeding treatment were purchased from the same local seed vendor as the container seedlings. The seeds were artificially stratified prior to sowing at the study site.

Experimental Design

The study was conducted as a randomized, complete block, split-plot design with four replications. The whole plots were the planting dates and the subplots were the stocktypes. Each subplot contained 25 planting positions. The seedlings and seed positions were on a 3-meter by 3-meter spacing. Seedlings were planted with a shovel and acorns were sown by hand to a depth of 5 centimeters. Two acorns were sown at each position. First-year survival and height measurements were taken in September, 1993. Analysis of variance was conducted using Statistical Analysis System Procedures (SAS Institute Inc. 1989). Results are discussed as significant at the 5 percent probability level.

RESULTS AND DISCUSSION

The bareroot seedlings were taller and had greater shoot and root mass than the container seedlings (table 1). Morphology recommendations for bareroot seedlings include heights greater than 46 centimeters, minimum root-collar diameters of 10 millimeters, and a well-developed root system (Kennedy 1993). An important distinction between stocktypes may be in their root characteristics. The bareroot seedling roots consisted primarily of a large tap root and a few primary and secondary laterals. The container seedling roots were fibrous, consisting of a tap root and many higher-order lateral roots. Container seedling production typically promotes fibrous root system development and protects these roots until planting (Landis and others 1990). Container hardwood seedlings, which experience lower handling stresses prior to planting, may have a better survival rate than bareroot seedlings on poor sites (White and others 1970). While bareroot production may also promote a fibrous root system, many of these roots can be lost during seedling removal from the nursery bed.

Table 1—Morphological comparison between 1-0 bareroot and 9-month-old container Nuttall oak seedlings prior to planting

Variable	Bareroot	Container
Height (cm)	56	46
Diameter (mm)	7.0	6.2
Root dry weight (g)	5.7	3.8
Shoot dry weight (g)	6.7	4.9

Soil moisture content (oven-dry basis) was about 40 percent for the January, February, and March plantings. Small portions of the site were ponded with rainwater, and the remainder of the soil on the site appeared to be near saturation. The original experimental design called for plantings to occur in April and May. However, above-average rainfall combined with high Mississippi River stages caused backwater flooding to occur at the study site. The seedlings planted in January, February, and March experienced flooding to a depth of 2 meters from late March to late May. For the June planting, soil moisture content in the root zone was about 28 percent. The soil was dry and cracked at the surface, typical for a montmorillonitic clay. Pettry and Switzer (1996) reported moisture contents in the root zone of forested Sharkey soils of about 51 percent and 41 percent for field capacity (.03 MPa tension) and permanent wilting percentage (1.5 MPa tension), respectively. Perhaps the discrepancies in soil moisture retention can be explained by the higher organic matter content that could be expected in a forest soil.

Survival was highest if the seedlings and seeds were planted in January and February (table 2). Survival was reduced significantly if the planting occurred in March or

Table 2—First-year height and survival of 1-0 bareroot, 9-month-old container and direct-seeded Nuttall oak seedlings planted on four different dates on a Sharkey clay soil series, Yazoo County, MS

Treatment	Total height	Height growth	Survival rate
	- - - *Centimeters* - - -		*Percent*
Planting date			
January 1993	31	2	62***
February 1993	33	1	58
March 1993	34	0	45
June 1993	32	-5	36
Stocktypes			
Bareroot	34***	-19**	38***
Container	46	3	84
Seed	15	15	30
Date and stocktype			
Jan-bareroot	35	-12	59
Jan-container	44	4	84
Jan-seed	14	14	44
Feb-bareroot	39	-14	56
Feb-container	46	3	80
Feb-seed	14	14	39
Mar-bareroot	37	-21	32
Mar-container	48	4	75
Mar-seed	16	16	28
Jun-bareroot	22	-31	4
Jun-container	48	3	95
Jun-seed	17	17	9

,* = Significant at the 1 percent and 0.1 percent probability level, respectively.

June. Overall, container seedlings had the best first-year survival, while direct seeding of had the worst. Direct seeding of bottomland oak species can be a low-cost and effective means of reforesting agricultural lands (Wittwer 1991, Bullard and others 1992, Stanturf and Kennedy 1996). However, adequate stocking by direct seeding may not be achieved because of seed predation, flooding, or drought (Johnson and Krinard 1987). Considering a recommended sowing rate of 3,600 seeds per hectare (Bullard and others 1992), stocking by direct seeding for the study site was about 1,100 seedlings per hectare after the first year. This is twice the minimum 550 seedlings per hectare usually recommended when planting bareroot seedlings for wildlife objectives. Seedling stocking could have been higher; however, many of our acorns sown prior to the flood were found on the soil surface or exposed in the soil cracks in June. Also, the small direct-seeded seedlings will be exposed to future floods and herbivory, probably further reducing the stocking. For reforestation projects initiated by Federal programs or regulation, adequate seedling survival usually must be guaranteed. The required seedling survival can range from 50 to 90 percent. Consequently, direct seeding, although relatively inexpensive, may be too risky for many bottomland hardwood wetland restoration projects.

Excellent survival can be achieved by planting bareroot seedlings, especially when environmental conditions are optimum (Allen 1990, Miwa 1995). For this study, the reduced survival rate for bareroot seedlings planted in March and June may be partially explained by the reduction in seedling viability during long-term cold storage. The long-term cold storage of hardwood seedlings should be avoided. Because of the height of hardwood seedlings, storage bags usually cannot be completely sealed. Long-term cold storage could result in the drying of the roots. Ideally, only the number of seedlings that can be planted in 1 day should be delivered from the nursery to the site (Kennedy 1993). However, nursery location, the size of the reforestation project, and delivery schedules may necessitate receiving all of the seedlings at one time. For large projects, the inability to plant all of the seedlings in a short time period will increase seedling storage time. In addition, planting delays caused by flooding may further keep the seedlings in cold storage. For the Lake George Project, delivery schedules, nursery location, and flooding kept large numbers of seedlings in cold storage for weeks prior to planting.

Flooding appeared to have less adverse effect on container seedling survival. Container seedling survival was higher than bareroot seedling survival when the planting occurred in January or February. In addition, the high June survival for container seedlings suggests that they can be kept in the containers and successfully established after the flood waters recede. The successful establishment of the June-planted container seedlings was achieved even though the seedlings were growing and evapo-transpirational demand on the site was high.

It was anticipated that the direct-seeded seedlings would be smaller than container or bareroot seedlings. However, the amount of stem dieback observed for the container and bareroot seedlings was disturbing. Bareroot seedlings were shorter after the first year in the field than when planted. Container seedlings were about as tall as when they were planted. Adequate survival is usually more important than rapid height and diameter growth for most bottomland hardwood restoration projects. However, the detrimental effects of complete inundation on seedling survival suggests that rapid height growth after planting is desirable.

CONCLUSIONS

First-year survival was highest when seedlings were planted during the conventional planting season. Container seedlings had the best survival regardless of planting date. Their apparent greater tolerance to flooding and handling stress, combined with better planting-time flexibility, may make container bottomland hardwood seedlings the best choice for the reforestation of sites prone to winter/early spring flooding.

ACKNOWLEDGMENT

Funding was provided by the U.S. Army Corps of Engineers Wetlands Research Program, U.S. Army Corps of Engineers Vicksburg District, and the USDA Forest Service. The research was initiated while the authors were employed by the U.S. Army Corps of Engineers, Waterways Experiment Station, Wetlands Branch.

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RELATIONSHIP BETWEEN FLOODING REGIME AND INCREASED HERBIVORY OF NUTTALL OAK

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Abstract—The atypical flooding of bottomland hardwood forests during periods of the year that historically did not experience flooding have been shown to have adverse physiological effects on even the most flood-tolerant species. A reduction in oxygen availability in the soil results in decreases of both photosynthesis and the production of compounds considered necessary for plant defense, which could potentially increase the rate of herbivory on flood-stressed individuals. This study examined the herbivory rates of tussock moth (*Orgyia leucostigma* J.E. Smith) caterpillars on Nuttall oaks (*Quercus nuttallii* Palmer) in a laboratory. Oaks were subjected to four different watering regimes: permanently flooded, intermittently flooded, flooded 10 centimeters below the soil surface, and well-watered controls. Normal plant growth and functioning were adversely affected by flooding. Photosynthetic rates in flooded plants were significantly reduced as compared to control plants. Control seedlings were significantly taller, possessed larger diameters, and had more leaves than seedlings subjected to flooding. Conversely, herbivory was greatest on permanently flooded Nuttall oak seedlings, indicating that flooded seedlings were more palatable to tussock moth larvae than seedlings that were not flood-stressed. This suggests that flooding, and the associated adverse effects on plant physiological functions, may predispose Nuttall oak trees to foraging arthropods. Factors affecting this predisposition are discussed.

INTRODUCTION

A common misconception relating to herbivorous arthropods inhabiting forested ecosystems is that all leaves are identical as a food source. However, leaf traits such as nutritional quality and secondary compounds considered important in plant defenses can be extremely variable. Variations are known to occur not only among individuals of the same host species (Pelham and others 1988, Senn and others 1992), but among leaves within the same host (Witham 1981, Schultz 1983). This variability results in a heterogenous environment in which populations of herbivores are not readily able to exploit (i.e., defoliate) an entire stand of trees or even an entire tree (Witham 1981 and 1983).

Variability in leaf quality can be related to several factors including the position of leaves in the canopy (e.g., sun versus shade leaf) (Field 1983), nutrient availability (Chapin and others 1987), leaf age (Raupp and Denno 1983, and references therein), or physiological stress (Rhodes 1983). Of these factors, physiological stress is likely to have the most dramatic impact on host variability and insect populations. Environmental stress (e.g., drought, freezing, and salinity) can increase the availability of essential nutritional macromolecules such as amino acids and sugars within plants (Levitt 1972, White 1984), and reduce the ability of plants to produce defensive chemicals (Rhodes 1979 and 1983). This increase in nutrients and decrease in defensive allelochemicals are likely induced by a reduction in photosynthesis in an attempt to reduce the potential of desiccation or accumulation of toxic byproducts in the plant (Kozlowski 1982a and 1982b). Price (1991, and references therein) summarizes this scenario as the plant stress hypothesis, which states that stressed plants exhibit a reduction in protein synthesis resulting in an increase in amino acids, and a decrease in the synthesis of defensive chemicals, which results in plants becoming more susceptible to herbivory (fig. 1). Furthermore, as susceptibility increases, herbivore populations are able to reach epidemic proportions after consecutive years of favorable conditions (e.g., leaf quality) for herbivores (Martinat 1987, Mattson and Haack 1987a and 1987b).

Although there have been numerous studies examining the relationship between physiological stress and herbivores (e.g., White 1976, 1984; Mattson and Haack 1987b), few studies have examined how flooding affects herbivores. Flooding does negatively affect the physiological functioning and growth of trees by causing root dysfunction (Kozlowski 1984, Pezeshki 1994), decreased photosynthetic rates (Pezeshki 1994), and decreased production of secondary compounds (Rhodes 1983). Overall variability in leaf traits may also be less pronounced

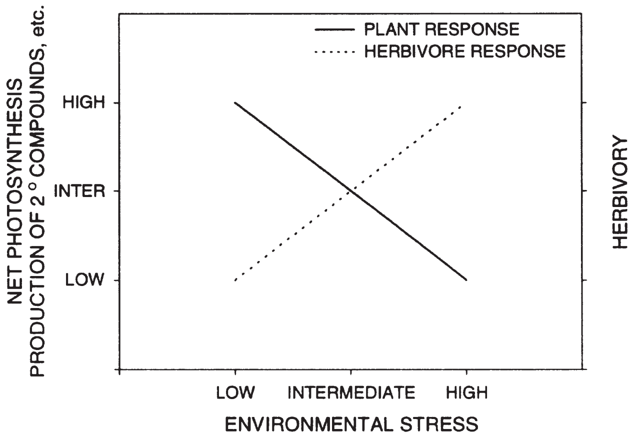

Figure 1—A generalized response of plants and herbivores to physiological stress (but see Bazzaz and others 1987).

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in flood-stressed plants, but little is known of how this and other flood-induced characteristics may influence increases or decreases in herbivory. There is little evidence of herbivory impacts in flooded forests, even in areas where flooding is quite common, such as in the lower Mississippi Alluvial Valley. Many of the bottomland hardwood forests found within this region are inundated for long periods of time due to natural flooding and human-induced changes in the landscape, resulting in the flooding of these systems during periods of the year when flooding was not historically common. These sometimes irregular and extended periods of flooding during the growing season may cause abnormal physiological stress on trees. However, population outbreaks of insect defoliators are historically quite rare in bottomland hardwood forests. The first recorded outbreak of forest tent caterpillars (*Malacosoma disstria* Hübner) in the Mississippi Delta occurred in 1989 (Leininger and Solomon 1995). This outbreak occurred in areas in and around the Delta Experimental Forest and the Delta National Forest. However, these areas are outside the levees, and although they are flooded during the fall and winter, they tend not to be flooded during the growing season; flood stress was not likely a factor in this outbreak. Very few other outbreaks have been documented in this region, although McCasland (1997) found an increase in the number of caterpillars in a year when flooding occurred versus the previous year when no flooding occurred. Thus the question arises, is flooding physiologically stressful enough to evoke a negative response from host species and are herbivores able to take advantage of flood-stressed individuals? The objective of this study was to evaluate the foraging response of a generalist herbivore species to various regimes of flooding of Nuttall oak (*Quercus nuttallii* Palmer), a tree species frequently found on poorly drained soils. Flooding regimes were designed to mimic the natural ranges of conditions experienced by this tree species within a bottomland hardwood forest.

METHODS

Forty-eight 2-year-old Nuttall oak seedlings germinated in a nursery were randomly assigned to one of four treatments: (1) control, well-watered but not flooded; (2) permanently flooded to 1 centimeter above soil surface; (3) intermittently flooded, 2 weeks of flooding followed by 2 weeks of drained, nonflooded conditions; and (4) partially flooded to 10 centimeters below the soil surface. Twelve seedlings were randomly assigned to each treatment and placed in a completely randomized block design. Plants were housed in a well-ventilated greenhouse.

Forty-four third instar white-marked tussock moth (*Orgyia leucostigma* J.E. Smith), (Lepidoptera: Lymantriidae) larvae were collected from oaks found in bottomland hardwood forests located in the Meeman Shelby Wildlife Management Area, and the Edward J. Meeman Biological Station, Shelby County, TN. Tussuck moths are quite common throughout most of North America and are known to feed on many species of trees, including oak (Van't Hof and Martin 1989). To assess the status of plant physiological functioning under various flooding regimes, net photosynthetic rates were measured using a portable gas exchange system (Model CIRAS12, PP System Inc., England). Net photosynthesis was measured on 12 sample leaves, one randomly selected leaf per each plant per treatment, prior to conducting herbivore studies. Herbivory experiments were conducted in a laboratory during the evening hours (2200-0200). One caterpillar was placed into a closed container with one randomly selected leaf from each of the four treatments. Leaves were placed randomly within one of four quadrants and a water dish was also placed within the container to maintain a constant moist environment. The area (square centimeters) of leaves were measured with a leaf area analysis system before and after the experiment. Herbivory was measured as the percentage of each leaf eaten by the caterpillar during the 4-hour experiment. Chemical analysis of leaf material was not conducted in this experiment. Therefore it was not possible to determine the presence and/or quantity of secondary compounds and nutrients, which play a major role in plant-herbivore interactions. However, the height, diameter, and final number of leaves produced at the end of the experiment were used as a measure of overall plant vigor, which is likely related to the quality of leaves as a food source for herbivores. One-Way Analysis of Variance (ANOVA) (SAS Institute 1989) was used to determine whether the net photosynthetic rates and the percentage of leaf area consumed differed among the four treatments. Tukey's Studentized Range Test was used to determine which treatments were significantly different from one another when there were overall significant differences among the treatments. The final heights, diameters, and number of leaves were strongly correlated with the initial heights and diameters of the seedlings (height $r = 0.7700$, $P = 0.0001$; diameter $r = 0.8416$, $P = 0.0001$; leaves $r = 0.4494$, $P = 0.0014$). Therefore, Analysis of Covariance was used, with the initial height as a covariate, to determine differences in heights and leaf numbers among treatments. Initial diameter was used as a covariate to examine differences in the mean final diameters among treatments.

RESULTS

Gas exchange measurements showed that net photosynthetic rates were reduced significantly ($F = 16.15$ $P < 0.0001$) in response to all three flooding regimes as compared to control plants (fig. 2). The amount of leaf area consumed differed significantly among the four treatments ($F = 4.23$; $P < 0.0001$). Herbivory was related to the amount and duration of flooding. Leaves from flooded plants were consumed significantly more than control leaves, and although not statistically significant, leaves from intermittently flooded trees were consumed more than leaves from trees subjected to partial flooding (fig. 2). Seedling heights, diameters, and the final number of leaves per seedlings were significantly different among treatments with control seedlings being taller ($F = 3.87$, $P = 0.0156$), possessing larger diameters ($F = 7.12$, $P = 0.0005$), and having more leaves ($F = 2.88$, $P = 0.0469$) than both permanently and intermittently flooded seedlings (fig. 3).

DISCUSSION

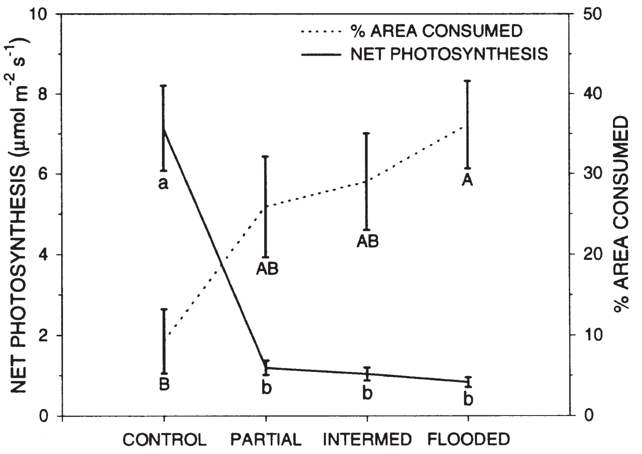

Figure 2—Net photosynthetic responses in Nuttall oak seedlings and percentage of leaf area consumed by tussock moths under various flooding regimes. Treatments with different letters are significantly different.

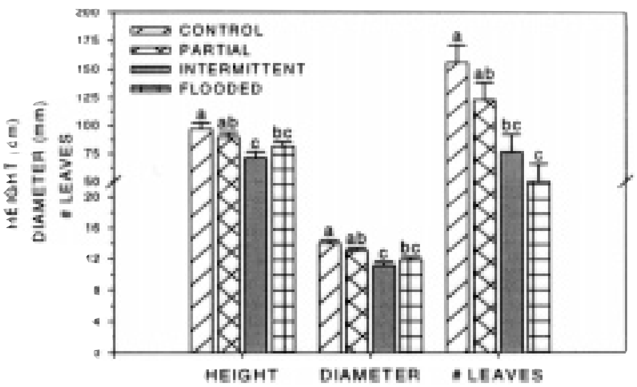

Figure 3—The mean final height, diameter, and number of leaves of seedlings subjected to each flooding treatment. Bars with different letters represent treatments that are significantly different.

The present study demonstrates that herbivory rates are affected by flooding in Nuttall oak seedlings. Leaves from seedlings that were flooded the entire length of the study were consumed most often, followed by leaves from trees flooded intermittently. It is apparent that these caterpillars chose flooded leaves above all other treatments. Although these leaves were not analyzed for nitrogen content or the presence of secondary compounds, treatments that were flooded exhibited decreased photosynthetic rates (fig. 2), low final heights, smaller diameters, and fewer leaves than nonflooded seedlings (fig. 3), thus further substantiating that these seedlings were stressed. Reduced photosynthesis is a common response to flooding for a majority of woody species studied (Kozlowski 1984). Such responses have been reported for flood-sensitive and flood-tolerant woody species (Pezeshki 1994, and references cited therein). Net photosynthetic rates were reduced in response to flooding, which suggests important implications for plant physiological functioning. It is possible that reduced net photosynthesis may have resulted in reduced production of secondary metabolites (Rhodes 1983, Estiarte and others 1994), which have been implicated in plant-herbivore defense mechanisms. For instance, phenolic compounds are critical in plant-herbivore interactions (Estiarte and others 1994). Many compounds that have been implicated in herbivore defense are metabolically costly to produce and may either be produced at a lower concentration or not at all under stressful conditions such as flooding when plants switch to anaerobic metabolism.

The significant differences between permanently flooded and control treated individuals in the amount of leaf area consumed and the net photosynthetic rate suggest that forests occurring in permanently flooded areas would have the highest potential impacts from herbivory. There is some evidence for this; for example, forest tent caterpillars in southern Alabama and Louisiana are known to reach epidemic populations in flooded tupelo (*Nyssa aquatica* L.) stands (Ciesla and Drake 1969). However, most bottomland hardwood forests are only temporarily flooded during the growing season. In addition, Nuttall oak does not typically occur in permanently flooded swamps (Filer 1990). There were no significant differences between the control and two intermediate flooding treatments in the leaf area consumed, which suggests that transitory flooding may not affect the relationship between flooding and herbivory. However, when the percentage of leaf area consumed is plotted against the net photosynthetic rate (fig. 2), it is obvious that leaves from any flooding regime were strongly selected over control leaves.

These results suggest that individuals that are exposed to irregular and moderate to prolonged flooding during the growing season may be adversely affected, not only because of the resulting reduction of carbon assimilation (Pezeshki 1994), but also due to a diminished capability to produce secondary metabolites for plant defense. Thus flooding can conceivably cause not only symptoms associated with root hypoxia, but also detrimental effects from defoliation. This reduction in defense and increase in herbivory could cause an increase in insect fecundity within the system, in addition to an increase in tree mortality from diseases linked to insect defoliation (Wargo 1977).

If this is the case, this phenomenon would be readily observable within bottomland hardwood forests found within the levee system of the lower Mississippi River. However, incidences of episodic outbreaks, or even local to moderate defoliation, have rarely been recorded. The question then arises, if a tree species that is readily found on poorly drained soils (e.g., at least moderately adapted to flooded conditions) exhibits the potential for an increase in herbivory related to flood stress, why are there so few documented occurrences? The likely explanation is that this study was conducted with 2-year-old seedlings. It is likely that even trees that are only a few years older (e.g., saplings) may exhibit temporary symptoms of flood stress, but once the roots begin to receive oxygen, the saplings are capable of quickly producing necessary defensive chemicals and, more importantly, converting important nutrients into substances less utilizable to herbivores. This situation is also more likely for older trees that have even more energy stored and are able to recover from the negative effects of flooding faster than seedlings and saplings. Therefore, it is likely that there is only a very narrow window of opportunity for arthropod populations to take advantage of flood stressed trees before they are able to return to preflooded conditions.

ACKNOWLEDGMENT

Funding for this project was provided by a grant from USDA National Research Initiative Competitive Grants Program, Grant # 91-37101-6905. We would also like to thank Peter Anderson for help with setting up the experiment and the collection of data, Chris Woodson for helping with the maintenance and watering, and Emile Gardiner, Ted Leininger, and Nathan Schiff for reviewing this manuscript.

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INTRASPECIFIC VARIATION IN THE ROOT ELONGATION OF BALDCYPRESS SUBJECTED TO SALINE FLOODING

Ken W. Krauss, Jim L. Chambers, James A. Allen, Brian Luse, and Antoinette Debosier[1]

SUMMARY

Many wetland forests in the coastal zone of southeastern Louisiana have been heavily stressed or destroyed by saltwater intrusion. Canal dredging, levee construction, coastal subsidence, and eustatic sea level rise all facilitate the intrusion of seawater into coastal swamp forests, resulting in widespread mortality of glycophytic wetland species. Although salinities in many of these areas are lower and the prospect for future amelioration projects are increasing, acute exposure to saline floodwaters from frontal passage or hurricanes will continue to cause mortality among both mature baldcypress (*Taxodium distichum* (L.) Rich.) and rejuvenating seedlings as long as avenues for saltwater intrusion remain. Researchers have recently focused on the identification of genotypes exhibiting greater tolerance to saline environments. The purpose of this study was to investigate intraspecific variation between progeny of five half-sib family collections of baldcypress from three freshwater and two brackish-water seed sources. Mini-rhizotrons were used to monitor root elongation for a period of 99 days while seedlings were subjected to three salinity levels under nonaerated, flooded conditions. Salinity produced significant species-level effects across all families, with root elongation decreasing with increasing salinity level. Family-level variation was significant as well, with relationships among families varying with treatment. In general, root elongation in families from brackish-water seed sources across all salinity treatments was greater than elongation for families from freshwater sources. Heights and diameters of the same seedlings were monitored for the first 62 days of salinity treatments. Species-level effects were significant for both parameters, but family-level effects were significant only for diameter. Intraspecific variation in root growth may prove to be a useful screening criterion for salt tolerance in baldcypress, since genotypes with greater potential for root development under saline conditions may experience better early survival and growth under saline field conditions.

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EFFECTS OF SEASONAL PRESCRIBED FIRES ON DENSITY OF HARDWOOD ADVANCED REGENERATION IN OAK-DOMINATED SHELTERWOOD STANDS

Patrick H. Brose and David H. Van Lear[1]

Abstract—Effects of seasonal prescribed fire on density of hardwood regeneration were investigated. Three mature mixed-oak (*Quercus spp.*) stands on productive sites were cut using a shelterwood technique, each forming a block of spring burn, summer burn, winter burn, and control treatments. Advance regeneration was inventoried from permanent plots before and after burning. Fires top-killed nearly all hardwood regeneration, forcing the rootstocks to sprout. All fire treatments significantly reduced red maple (*Acer rubrum*) and yellow- poplar (*Liriodendron tulipifera*) densities, primary competitors of oak, for at least 2 years, while oak density was unaffected. Hickory (*Carya spp*) responded to fire similarly to oak. The competitive position of oaks in the advance regeneration pool was enhanced by all fire treatments, spring burning providing the most benefit.

INTRODUCTION

For the past several decades, resource managers have struggled to regenerate oak stands on productive upland sites (Lorimer 1993). This problem has been the subject of numerous conferences and scientific publications. The shelterwood system is often recommended as a technique to promote oak regeneration when it is lacking on productive sites (Sander and others 1983) but often fails because conditions conducive to oak regeneration development stimulate intense competition from less-desirable species (Loftis 1983, Sander 1979, Schuler and Miller 1995).

Supplemental treatments are sometimes prescribed before the initial shelterwood cut, to reduce or eliminate the anticipated competition problem. Loftis (1990) and Lorimer and others (1994) clearly demonstrated the value of competition control with herbicides but this approach is expensive: $70 per acre or more. Barnes and Van Lear (in press) tested understory prescribed burning to accomplish the same task as herbicides and found favorable results but needed multiple burns over several years to obtain similar results.

Hannah (1987) suggested prescribed fire may be an appropriate follow-up treatment to shelterwood harvesting. In 1993, the Virginia Department of Game and Inland Fisheries (VDGIF) tried this approach in a pilot study and found summer burning greatly reduced densities of less-desirable hardwoods, i.e., red maple, sweetgum, and yellow-poplar, more than densities of oak and hickory (Keyser and others 1996).

In this study, we expanded upon VDGIF's pilot study by examining effects of prescribed fire in different seasons on density of advance regeneration of common hardwood species in 2- and 4-year-old shelterwood stands. We hypothesized that prescribed burning of shelterwood stands would reduce densities of red maple and yellow-poplar more than oak, thereby improving oak's competitive position in the advance regeneration pool.

METHODS

Study Area

This study was conducted at the Horsepen Wildlife Management Area in the Piedmont of central Virginia. This area consists of broad, gently-rolling hills with Cecil sandy loam soils (Typic Hapludult). Climate is warm continental with 50 inches of annual precipitation distributed evenly throughout the year and an average growing season of 190 days (Reber 1988). The area is presently owned and managed by VDGIF.

Three mature hardwood stands, cut to shelterwoods 2 to 4 years earlier, were selected in 1994 for the study. According to VDGIF records, the stands had similar site characteristics and species composition before the initial harvest. Average site index 50 for oak was 75 feet and basal area was 110 square feet per acre.

Common overstory trees were, in order of decreasing abundance, white oak (*Quercus alba*), yellow-poplar, northern red oak (*Q. rubra*), black oak (*Q. velutina*), scarlet oak (*Q. coccinea*), pignut hickory (*Carya glabra*), mockernut hickory (*Carya tomentosa*), and chestnut oak (*Q. prinus*). Their ages ranged from 90 to 110 years. Common midstory hardwoods included, in order of decreasing abundance, red maple, blackgum (*Nyssa sylvatica*), flowering dogwood (*Cornus florida*), American beech (*Fagus grandifolia*), and ironwood (*Carpinus caroliniana*).

Harvesting removed poor quality oaks and low value species leaving 50 percent canopy opening. Two stands were harvested in summer 1990 and the third in winter 1992. Slash was left in place. Volumes removed averaged 6 mbf per acre and residual basal areas averaged 41 square feet per acre.

Study Design and Sampling

A randomized complete block design was used to analyze season-of-burn effects on density of advance regeneration. Each stand was divided into four 4- to 10-acre treatment

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areas (winter burn spring burn, summer burn, and an unburned control). Fifteen circular, 212 square feet plots were systematically located in each treatment area. Advance regeneration stems between 1.0 and 10.0 feet tall were tallied in each plot in fall of 1994 and 1996. Stems were recorded as hickory (mockernut and pignut), mixed oak (black, chestnut, northern red, scarlet, and white), red maple, and yellow-poplar. Multiple stems arising from the same rootstock were counted as one stem.

Prescribed Fires

The prescribed fires were conducted on February 25 and 27 (winter burn), April 26 (spring burn), and August 24 (summer burn), 1995 by VDGIF personnel in accordance with department policy and state law. Weather conditions varied among seasons but were considered typical. All prescribed fires were ignited by hand with drip torches in a strip-head fire pattern commencing at the downwind side of the treatment. Ignition strips were initially spaced 10- to 15-feet apart and this spacing gradually widened to 50 feet once existing firelines were strengthened. Spring fires produced the most intense fire behavior with flame lengths and rates of spread averaging 3.5 feet and 5.0 feet per minute, respectively. Winter and summer fires behaved similarly to spring fires when weather conditions permitted, but increases in relative humidity and decreases in wind reduced fire behavior to 1- to 2-feet flame lengths and 1- to 3-feet per minute rates of spread. Overall, prescribed burns were easily executed and behaved typically of fires in oak forests.

Statistical Analysis

Differences in species densities within treatments were detected using analysis of variance with Duncan's multiple range test (alpha = 0.05) (SAS 1993). Changes in species' densities after treatments were similarly tested. Treatments were compared through covariance analysis of declines in species densities with preburn densities as a covariate (SAS 1993). Data were rank-transformed to correct unequal variances and nonnormality.

RESULTS AND DISCUSSION

Treatment Effects on Species

No block effect was found among stands allowing data to be pooled to decrease variance and simplify reporting. Before burning, yellow-poplar dominated all treatments, averaging over 2,900 stems per acre (table 1). Red maple was the second most abundant species, 1,607 stems per acre, with hickory and mixed oak being least common (843 stems per acre).

Relative differences among species did not change in the control treatments during the 2 years of the study (table 1). Yellow-poplar continued as the most abundant species (2,249 stems per acre), followed by red maple (1,789 stems per acre). Hickory and mixed oak were least common, averaging 622 stems per acre.

Table 1—Mean densities (stems per acre ± 1 st. error) of hardwood regeneration before and 2 years after seasonal prescribed fires in oak-dominated shelterwood stands; densities followed by different letters are different within that treatment (alpha = 0.05)

Treatment and species	Preburn	Postburn
Control		
Hickory	760±85c	666±95c
Mixed oak	639±66c	578±103c
Red maple	1809±283b	1786±204b
Yellow-poplar	2256±529a	2249±450a
Winter burn		
Hickory	733±100c	805±140b
Mixed oak	717±75b	1197±68a[a]
Red maple	1539±124b	1138±126a[b]
Yellow-poplar	2960±497a	1302±190a[b]
Spring burn		
Hickory	918±97c	846±88b
Mixed oak	962±107c	1363±209a[a]
Red maple	1807±168b	994±168b[b]
Yellow-poplar	2389±324a	849±179b[b]
Summer burn		
Hickory	783±87c	562±93b[b]
Mixed oak	1230±220b	1166±153a
Red maple	1273±196b	684±104b[b]
Yellow-poplar	4031±657a	1103±243a[b]

[a] Indicates an increase from preburn density (alpha = 0.05).
[b] Indicates a decrease from preburn density (alpha = 0.05).

Winter fires reduced yellow-poplar density from 2,960 to 1,302 stems per acre, a 56 percent loss (table 1). Red maple decreased to a lesser degree, from 1,539 to 1,138 stems per acre (26 percent reduction). Oak density increased by 480 stems per acre and hickory density was unchanged. Two years after winter fires, mixed oak, red maple, and yellow-poplar had equivalent densities with hickory being less numerous.

Spring burning decreased yellow-poplar density by 65 percent, from 2,389 to 849 stems per acre (table 1). Red maple density was reduced from 1,807 to 994 stems per acre (45 percent loss). Oak density increased by 400 stems per acre and hickory density was unchanged. Two years after spring fires, mixed oak outnumbered all other species.

Summer burning reduced densities for all species except oak (table 1). Yellow-poplar declined from 4,031 to 1,103 stems per acre (73 percent loss) while red maple was reduced 46 percent from 1,273 to 684 stems per acre. Hickory decreased by 220 stems per acre (28 percent). Oak density was unchanged. Two years after summer fires, oak and yellow-poplar had equivalent densities, outnumbering hickory and red maple.

Oak and hickory regeneration are apparently more capable of sprouting following fire than red maple and yellow-poplar reproduction of comparable stem size. This may result from seed caching by wildlife and differences in germination strategy, i.e., hypogeal versus epigeal. Sound acorns are routinely buried in the forest floor by birds and small mammals (Galford and others 1988) while red maple and yellow-poplar seeds remain at or near the surface (Beck 1990, Walters and Yawney 1990). Acorns have hypogeal germination (Rogers 1990, Sander 1990), causing the root collar to be below the soil surface (protected from fire), while red maple and yellow-poplar seeds have epigeal germination, placing the root collar at or near soil surface (exposed to fire). Dormant buds at the root collar are essential for sprouting following top-kill so oak and hickory rootstocks were better protected than those of red maple and yellow-poplar. Examined roots of dead red maple and yellow-poplar revealed shallow roots which may have been damaged by the downward heat pulse. It was also observed that new oak sprouts came from below groundline while new red maple and yellow-poplar sprouts originated at or above groundline.

Differences in growth strategies between oak and its competitors also probably contribute to fire selecting against red maple and yellow-poplar. Oaks have a conservative growth strategy of emphasizing root development in lieu of rapid shoot elongation while many competitors take the opposite approach (Kelty 1988, Kolb and others 1990). Because spring burning occurred when leaves were 50 to 75 percent expanded, root reserves of all species were low. However, despite leaf expansion, the larger roots of oaks apparently still contained more carbohydrates with which to sprout than those of red maple and yellow-poplar. These energy reserves helped prevent declines in oak density while competitors lacking such reserves had large losses.

The increase in oak density from 1994 to 1996 was due to previously uncounted small stems sprouting and vigorously growing into the sampling strata (1.0 to 10.0 feet). No mass germination of yellow-poplar occurred despite its abundance in the overstory prior to harvest. Apparently, its soil seed bank was exhausted in the initial germination and removal of mature yellow-poplars prevented additional seed storage during the years between harvest and prescribed burning.

Comparison of Treatments

After adjusting for preburn differences in species density, growing-season fires (spring and summer) were more lethal to most species than winter fires (table 2). Yellow-poplar density declined 1,700 stems per acre in spring and summer fires, significantly more than winter fire (1,134 stems per acre). Also, yellow-poplar was more sensitive than oak to any seasonal fire. Spring and summer fires decreased red maple density about 587 stems per acre, nearly three times more than winter burning (219 stems per acre). Red maple differed from oak only in spring and summer fire treatments. Hickory was reduced more by summer burning (688 stems per acre) than by spring or winter burning (264 stems per acre each) with summer fire being more lethal to hickory than to oak. Likewise, oak was more affected by summer burning, a reduction of 455 stems per acre, than by winter or spring fires (217 stems per acre loss). All fires caused greater mortality than not burning for all species.

The clear difference in hardwood competition control between winter burning and both growing-season fires is due to regeneration being physiologically active during the spring and summer (Hodgkins 1958) and is well documented in southern pine ecosystems (Langdon 1981, Waldrop and others 1987).

Spring fires provide the greatest improvement in the competitive position of oak in the advance regeneration pool because it maximizes reduction of red maple and yellow-poplar with minimal loss of oak. Opportunities for spring burning are common due to high insolation levels, warm temperatures, southerly winds, and low humidities. Drawbacks to spring burning are increased probability of fire escape and overstory tree damage/mortality due to burning during the natural fire season of Eastern North America.

Table 2—Adjusted declines in densities (stems per acre) of hardwood regeneration following seasonal prescribed fires in oak-dominated shelterwood stands; densities followed by different letters are different for that species (alpha = 0.05)

Treatment	Hickory	Mixed oak	Red maple	Yellow-poplar
Control	35c	32c	33c	26c
Winter burn	260b	215b	219b	1134b[a]
Spring burn	268b	219b	577a[a]	1688a[a]
Summer burn	688a[a]	455a	597a[a]	1713a[a]

[a] Indicates that adjusted density decline of species is greater than that of oak for the same treatment (alpha = 0.05).

Summer fires are comparable to spring burning with less risk of fire escape. The reduced shade in shelterwoods and increased fuel load from the initial cut makes burning them possible when surrounding uncut areas are not highly flammable. However, winds must be moderately high (5 to 10 miles per hour) and fine fuels dry (10 to 15 percent) to counter the presence of partial shade. Another drawback to summer burning is increased oak mortality relative to other seasons.

Winter burning enhances the competitive position of oak in the advance regeneration pool but not as successfully as growing-season fires. Numerous winter fires are needed to accomplish the competition control possible with a few growing-season burns (Barnes and Van Lear 1997, Langdon 1981, Waldrop and others 1987).

CONCLUSIONS

This study supports our hypothesis that prescribed fire enhances the competitive position of oak in the advance regeneration pool. Prescribed burning of these shelterwood stands was definitely a step in the right direction. Whether this reduction in competition density is enough to produce oak-dominated stands on these productive sites in the future is unknown. Long-term monitoring of these stands is a must as red maple and yellow-poplar are still common and vigorously growing. Additional prescribed fires may be needed, depending on development of the regeneration during the establishment phase. Regardless of whether single or multiple fires are needed to ensure eventual oak domination, this shelterwood—burn prescription is a promising approach to regenerating oak stands on productive sites.

The density reduction of yellow-poplar and red maple has important implications for resource managers. Most importantly, this approach provides managers a simple and environmentally sound way to regenerate oaks on good sites. In addition, residual overstory trees can be harvested to create an evenaged early-successional habitat or retained for a second rotation to make a two-storied stand. If retained, some may die, becoming snags for wildlife while they stand and later, downed woody debris. Reapplication of growing-season fire at frequent intervals (annual or biennial) would eventually lead to an oak-dominated savanna (Thor and Nichols 1973), benefitting numerous plant and wildlife species. In short, this approach favors oak advance regeneration on productive sites, a critical first step in regenerating oak stands (Sander 1971, Sander 1972), and may be appropriate for a wide array of natural resource interests.

More research of the fire-oak relationship is warranted to answer questions arising from this study. Results of this method from other physiographic regions and forest types of North America would be valuable. What are the implications of this approach to understory plants and wildlife species? Will the short-term benefits shown in this study ensure long-term success? There is a place for prescribed fire in hardwood management. However, guidelines still need to be developed for managers attempting to maintain oaks on productive sites.

ACKNOWLEDGMENT

The authors gratefully recognize the assistance and support of the Virginia Department of Game and Inland Fisheries, especially Patrick Keyser, Wildlife Biologist, in this study. We also thank Peter Kapeluck and Thomas Waldrop for critical reviews of earlier versions of this manuscript. Financial support provided by McIntire-Stennis funding is gratefully acknowledged.

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USE OF PRESCRIBED FIRE TO PROMOTE OAK REGENERATION

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Abstract—A 25-acre, 61-year-old planted slash pine (*Pinus elliottii* Engelm.) stand with yellow-poplar (*Liriodendron tulipifera* L.) and other hardwood volunteers on highly erosive, former agricultural land in the Coastal Plain of West Tennessee was burned three times at 3-year intervals from 1986 to 1992 primarily for enhancement of wildlife habitat, fuel reduction, and control of competing vegetation. A secondary effect of the burning regime was the unplanned development of advance oak (*Quercus* spp.) reproduction from 3 feet to 5 feet in height. Because of the fortuitous amount of oak advance reproduction and the relative absence of other residual species, the entire stand was harvested to release the oak. One-half of the stand was burned again in March 1995 to suppress current year (1994) natural seed from the pine and poplar before the complete harvest in the summer of 1995. Seventy-five permanent plots were established to survey regeneration before and after the harvest. This study presents comparisons of first-year data on amount, form, and composition of regeneration between the recently burned and unburned areas with respect to advance oak reproduction. The burning regime has maintained oak as advance reproduction and limited the amount of yellow-poplar.

INTRODUCTION

Although oaks make up the majority of the overstory across the Eastern United States, silviculturists continue to have difficulty in securing adequate oak regeneration on the better sites. A recent symposium (Loftis and McGee 1993) addressed the problems and opportunities associated with oak regeneration. Success in promoting oak regeneration requires (1) large seedlings capable of fast growth, whether that be from advance regeneration (Loftis 1990) or the planting of physiologically superior seedlings (Pope 1993); and (2) control of competing vegetation.

Fire also appears to have been an important factor promoting oak regeneration and dominance in pre- and postsettlement forests (Abrams 1992, Crow 1988). Fire encourages oaks by reducing competition from fire-intolerant species as well as enhancing oak regeneration through its tenacious ability to root sprout repeatedly following top-kill in frequent fire regimes (Van Lear and Watt 1993). Several authors have suggested that the suppression of fire in recent years has limited oak regeneration (Abrams 1992, Lorimer 1993, Van Lear and Waldrop 1989). Although research has not yet identified a regime for the use of fire in promoting oak regeneration, a series of burns rather than a single burn during the preharvest period will likely be required to favor oak regeneration (McGee 1979, Merritt and Pope 1991).

In Tennessee, many oak forests are regenerating after harvest to yellow-poplar, especially on the better sites. To have oak forests on the better sites, oak regeneration and growth should be promoted, while yellow-poplar should be controlled. A regime of prescribed burning may be part of the answer.

This study capitalizes on a planted bottomland pine stand with a yellow-poplar component that was burned at 3-year intervals for the last 9 years. The prescribed burning regime probably influenced the fortuitous amount of oak regeneration and the scarcity of other species in the understory. However, yellow-poplar was still a concern because, even germinating from seed, poplar generally outgrows oak seedlings (O'Hara 1986). Poplar seed accumulating since the previous burn remains viable in the duff for many years (Clark and Boyce 1964). Fifty percent of the stand was burned again before harvest to control yellow-poplar seed and seedlings. The objective of the study was to compare oak regeneration and its competitiveness with yellow-poplar on recently burned and unburned areas 1 year after the harvest.

STUDY AREA

The study was conducted on a 25-acre stand planted with slash pine at Chickasaw State Forest (CSF) in Chester County, TN, located approximately 20 miles south of Jackson in southwestern Tennessee and managed by the Tennessee Division of Forestry. Soils are Typic Fragiudults (Savannah series), formed in loamy Coastal Plain deposits, severely eroded, moderately drained, slowly permeable, and occasionally flooded with a perched seasonal water table above the fragipan. The study area is on a convex slope (2 to 5 percent) of a terrace near a second-order stream that flows to the Hatchie River. Annual precipitation averages 50 inches, usually evenly distributed in all seasons. Average site index (base age 50) for loblolly pine (*P. taeda* L.) ranges from 80 to 90 feet (Ditzler and others 1994).

The CSF was part of the federal Resettlement Administration purchase of land during the mid-1930's. The study area was a severely eroded, abandoned agricultural field with numerous gullies and ditches. Slash pine was planted to control the erosion. Since that time, the study area remained relatively undisturbed until a 3-year interval of prescribed burning was initiated during the winter of 1985-1986. No other cultural treatments or thinnings had occurred. In March 1995, the stand was 61 years old with over 17,000 board feet per acre. Stand basal area averaged 135 square feet per acre. Slash pine composed 66 percent of the stems 8 inches and greater in diameter, and 79 percent of the volume (table 1). Other overstory tree species that naturally invaded the

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Table 1—Number of trees and volume by species present on the study area at Chickasaw State Forest before the harvest cut in 1996

Species	Trees		Volume[a]	
	No.	*%*	*Board ft*	*%*
Slash pine	1,069	66	376	79
Shortleaf pine	97	6	26	5
Yellow-poplar	185	11	36	8
Sweetgum	171	10	24	5
Red oak	38	2	7	1
Miscellaneous[b]	61	4	6	1
Total	1,621		475	

[a] International 1/4 inch Rule.
[b] Miscellaneous includes white oak, post oak (*Q. stellata* Wangenh.), hickories (*Carya* spp.) red maple, black cherry (*Prunus serotina* Ehrh.), and blackgum (*Nyssa sylvatica* Marsh.).

study area were yellow-poplar, shortleaf pine (*P. echinata* Mill.), sweetgum (*Liquidambar styraciflua* L.), red maple (*Acer rubrum* L.), various red oaks (*Q. rubra* L., *Q. phellos* L., *Q. falcata* var. *pagodaefolia* Ell., *Q. shumardii* Buckl.) and white oak (*Q. alba* L.).

In 1994, the stand was being considered for a timber sale. At that time, CSF managers noticed an inordinate amount of advance oak regeneration that was taller than 3 feet and a scarcity of other advance regeneration, particularly yellow-poplar. Since this area probably was a bottomland hardwood stand before cultivation, the opportunity was present for a conversion from planted pine to bottomland hardwoods.

METHODS

The chronology of management activities (burns, regeneration surveys, and timber harvest) in this stand is shown in table 2. Seventy-five permanent plots were established over the 25-acre area on a 120 by 120 foot grid. Regeneration was surveyed before and after the harvest cut by species and height classes (less than 1 foot, 1 to 3 feet, and greater than 3 feet). Plot size was 0.02 acre. In the two treatments (burned and unburned in 1995), 43 plots on 14 acres provided the sample of the burn treatment and 32 plots on 11 acres provided information on the unburned treatment. Data are presented for the regeneration present in 1994, before the 1995 burn and harvest, and in the fall of 1996, one growing season after the harvest.

RESULTS

Initial Survey in October 1994

Three growing seasons after the 1992 prescribed burn and before the timber harvest, the stand contained an average of almost 5,800 woody stems per acre (advance reproduction) that were less than 2 inches in diameter and less than 8 feet tall (table 3). Oaks composed nearly 26 percent of the total stems, most being over 1 foot in height.

Table 2—Chronology of events on the study site at Chickasaw State Forest

Event	Time of occurrence
Prescribed fire (all winter/spring burns)	1986, 1989, 1992
Regeneration survey	Oct. 1994
Prescribed fire (50 percent of area)	Mar. 1995
Timber harvest	Aug. 1995
Remaining residuals >2 inches slashed	Winter 1995-1996
Regeneration survey (2 treatments)	Oct. 1996

Table 3—Regeneration survey of the study area at Chickasaw State Forest 1 year before the harvest cut and one year after the harvest cut

Treatment	Regeneration survey Oct. 1994		Regeneration survey Oct. 1996	
	#/acre	*%*	*#/acre*	*%*
Burned (n=43)				
Oaks	1,714	28.8	1,690	17.8
Yellow-poplar	557	9.4	482	5.1
Sweetgum/red maple	1,299	21.9	2,529	26.7
Miscellaneous[a]	2,372	39.9	4,787	50.4
Total	5,942		9,488	
Unburned (n=32)				
Oaks	1,263	22.7	1,326	12.5
Yellow-poplar	601	10.8	881	8.3
Sweetgum/red maple	1,170	21.0	2,956	27.8
Miscellaneous[a]	2,527	45.4	5,452	51.4
Total	5,561		10,615	

[a] Miscellaneous includes pines, blackgum, black cherry, dogwood (*Cornus florida* L.), river birch (*Betula nigra* L.), sourwood (*Oxydendrum arboreum* (L.) DC.), elms (*Ulmus* spp.), sassafras (*Sassafras albidum* (Nutt.) Nees), sumacs (*Rhus* spp.), alder (*Alnus* spp.) and several other species as minor components.

Yellow-poplar was a minor component of the understory (10 percent), while the miscellaneous species category, consisting primarily of pines, dogwood, elms, and sumacs, had over 40 percent or the majority of the stems. Sweetgum and red maple had fewer stems than the oaks at 21 percent.

Effects of Burn Treatment

Reproduction in the burn treatment measured 1 growing season after the harvest cut, yielded over 9,400 stems per acre (table 3). While numerous oaks were present, the percentage of oaks in the treatment (17.8 percent) was less than that in the initial stand before the harvest and 1995 burn (28.8 percent). The number of sweetgum/red maples and miscellaneous species doubled. Yellow-poplar seedlings decreased initially from 9.4 percent to 5.1 percent in the burn treatment even though the number of seedlings remained similar. The yellow-poplar stems found in the burn treatment were almost exclusively from stump sprouts of harvested stems.

Effects of Unburned Treatment

The total number of stems in the unburned treatment essentially doubled over the study period (table 3). Oaks maintained their numbers and decreased drastically as a percentage of total stems (22.7 to 12.5 percent). Yellow-poplar increased slightly, primarily from stump sprouts after the harvest and from seedlings that remained from the initial survey. Sweetgum/red maple and miscellaneous species both more than doubled their number.

Burned versus Unburned Treatments

The number of oak stems, regardless of treatment, remained similar to the 1994 survey (table 3). Yellow-poplar decreased with burning and increased with the unburned treatment. Regeneration stem counts for sweetgum/red maple and the miscellaneous category doubled over the study period. Most stems in the 1996 survey were 1 to 3 feet tall regardless of species and treatment.

DISCUSSION

First-year results indicate that the burn treatment has maintained the oak advance regeneration component and slightly reduced it for yellow-poplars. Oaks persist following burning due to their ability to resprout repeatedly after top-kill from suppressed buds at or below the ground level. This vigorous resprouting precludes the establishment of most other competing species (Clatterbuck 1990). The prescribed burning regime before the harvest favors the advanced reproduction and establishment of oaks, giving them an ecological advantage over other species (Van Lear and Waldrop 1989).

One year after harvest, the regeneration count for sweetgum and red maple was essentially the same for the burned and unburned samples. The number of stems doubled from the initial survey regardless of treatment. Both sweetgum and red maple are light-seeded species that invade recently harvested areas. Sweetgum also has the ability to root sprout from suppressed root buds (Kormanik and Brown 1967), while red maple readily stump-sprouts (Hutnick and Yawney 1961). Sweetgum and red maple colonize disturbed areas quickly from both seed and sprouts and tend to dominate during the early stages of succession. However, within a few years, oaks and yellow-poplar usually stratify above these species relegating them to a subordinate position (Clatterbuck and Hodges 1988, O'Hara 1986, Oliver 1978). Red maple and sweetgum, although present in the stand before the harvest, constituted less than 1 percent of the overstory stems and volume (table 1).

Miscellaneous species are composed primarily of noncommercial timber species that remain in the midcanopy layers. Although numerous, these species are not expected to gain prominence over time. Most will be overtopped by oaks, yellow-poplar, sweetgum, and red maple. Species composition in the miscellaneous category shifted somewhat in the initial survey from dogwood, sourwood, elms, and blackgum to the pioneer species such as black cherry, river birch, sassafras, and sumacs in both treatments after the timber harvest. There was little difference in total number of seedlings in the miscellaneous classification between treatments.

The purpose of the burn treatment before the harvest cut was to eliminate the seeds of yellow-poplar and pine that had accumulated on the forest floor since the prescribed burn in the spring of 1992. The yellow-poplar in the unburned treatment had a 4-year seed bank, while those in the burn treatment had seed fall for 1 year. Fire eliminated most of the "from seed" yellow-poplar seedlings that were in the burn treatment. Most seedlings in the burn treatment were from stump sprouts from the logging and slashing activities. Those in the unburned treatment were both from new seedlings that had accumulated over 4 years and stump sprouts from the harvest cut.

SUMMARY

First-year results indicate that the burning regime of repeated prescribed fire enhanced the regeneration of oaks, especially in developing adequate and vigorous advance reproduction. With burning, the oaks had an advantage in their early development compared to other species. Burning tended to reduce yellow-poplar seedling density, but this was confounded with stump sprouting after the harvest. These results should be evaluated, recognizing the rapid growth of yellow-poplar on these good sites. Follow-up studies are planned using these permanent plots to see if whether oaks will maintain their early advantage or be displaced by yellow-poplar or other species.

ACKNOWLEDGMENT

Appreciation is expressed to Mr. Roy Ward and Mr. Steve Grayson of the Tennessee Division of Forestry, Forest Managers at Chickasaw State Forest, for their field and data assistance.

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