

Stand Development and Dynamics

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VALUE OF TREE MEASUREMENTS MADE AT AGE 5 YEARS FOR PREDICTING THE HEIGHT AND DIAMETER GROWTH AT AGE 25 YEARS IN LOBLOLLY PINE PLANTATIONS

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Abstract—Early growth measurements of pine plantations are often used to predict the productivity of the stand later in the rotation when assessing the effect of management on productivity. A loblolly pine (*Pinus taeda* L.) study established at 36 locations (2 to 3 plots/location) was used to test the relationship between height measurements at age 5 years and productivity at age 25. Mean heights of dominant and codominant trees at age 25 were used to represent site index at a location; basal area growth per tree from ages 20 to 25 was used as an index of individual tree growth.

The plot data showed a relatively weak relationship ($r^2=0.40$) between heights at age 5 and site index. Ranking age-5 heights and using only taller trees did little to improve the relationship. The fit of the regression equation changed gradually from an r^2 of 0.45, when only the tallest tree was used, to an r^2 of 0.43 when the tallest one-half of all trees was used. Using more trees did not degrade that relationship. As all trees must be measured to determine the tallest group, little is gained by attempting to designate dominant and codominants or crop trees for use in analyses and interpretations. Overall, predictions of stand productivity at age 25 using only individual tree parameters based on height at age 5 were of little value, accounting for only about 20 percent of the variation. Although plot location and rank of the tree within a plot each accounted for about 10 percent of the variability at age 25, a nearest-neighbor competition index and height at age 5 accounted for less than 0.1 percent each. However, rank by height at age 5 was an excellent predictor of individual tree survival, with 95-percent survival at age 25 for the tallest pines and almost no survival for the shortest pines. Based on the results of this study, we surmise that accurate modeling of stand development from early measurements probably requires more site information, such as amount and type of competing vegetation, soil properties, and a history of the land management.

INTRODUCTION

A major problem in evaluating new techniques for pine stand establishment and management manipulation is the long time required for the crop to reach harvest age. Even in short-rotation, intensively managed plantations, the rotation period closely matches that of scientists' careers. Thus, there is a need to reliably use early measurements to make projections about subsequent stand development. While there are several ways to make projections, the methods have not been validated.

Equations developed from site index curves can be used to predict relative growth at later ages from early measurements. This method has several disadvantages. First, local curves may not be available, and regionwide curves must be used (Shoulders 1976). Second, site index curves may be valid only for older stand ages and not be useful below age 10 (Farrah 1973). Third, when anamorphic site index curves are used, projecting heights from a young age to a site index is simply multiplying the mean heights by a constant. Thus, the manipulation adds no new information or changes the relative differences between treatment means. Finally, the use of anamorphic curves is based on the assumption that relative rates of growth are constant, and the falseness of this assumption is shown by studies in which treatments did change the rate of height and diameter growth (Cain 1978).

Identifying crop trees using heights at age 5 or other measurements from early ages is another method sometimes used to project stand development forward. The crop trees are trees in the stand at the early

measurement period that are expected to develop into dominants and codominants at rotation age. The crop trees may be identified as a fixed percentage of the number of living trees or on a fixed-area basis such as using the tallest 247 trees per ha (Mann and Derr 1970). One disadvantage of this method is that the size of the neighboring trees is not taken into account. Secondly, like the anamorphic site index curves, the method assumes that all trees develop at the same rate. Wakeley (1971) found that trees of superior size at age 30 were usually of above-average size at early ages. However, a number of trees changed from being below average at younger ages to superior at age 30. There were sufficient trees in the late-surgling population so that the correlations of heights at age 30 to heights at age 5 ranged from 0.31 to 0.47 for loblolly pines (*Pinus taeda* L.).

In a preliminary examination of a loblolly pine data set, we also found that using plot means of heights at age 5 was a poor predictor of the actual site index (base age 25) on the same plots, accounting for only 40 percent of the variation. In this paper, we are using data from plantations located on a wide range of sites and measured over a period of 25 years to examine ways of using early measurements in predicting the size of the stand at later ages. First, we use ranked heights of all the trees on each plot to find the optimum number of large trees to identify as crop trees. Secondly, we use the heights, rank within the stand, competition index of nearest neighbors, and stand location to evaluate which tree and stand parameters at young ages are the most useful in predicting future tree size, stand structure, and survival.

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METHODS

Sites and Measurements

The data set used is a subset of a larger one from a study that compared the performance of different pine species on a wide range of sites in Louisiana and Mississippi (Shoulders 1976). Originally, 47 sites were planted in Louisiana in 1954-58 with each site consisting of three replicates each of loblolly, slash (*P. elliottii* Engelm.), and longleaf pine (*P. palustris* Mill.). Shortleaf pine (*P. echinata* Mill.) was also planted at some of the northern Louisiana locations. The sites were mostly on open, cutover forest land that had not been tilled but had been kept in grass by frequent fires after the original forest was cut in the 1920's. Each plot consisted of 11 rows of 11 trees planted at a 1.83-m spacing. Seedlings grown from unimproved seed lots in a State nursery were graded by Wakeley's (1954) rules, and only seedlings graded 1 or 2 were used. Only the loblolly data collected in Louisiana are used in this paper. By age 25, only 29 of the sites still had all three replicates with sufficient surviving loblolly pines to measure, 5 sites had two surviving replicates and 2 sites had only one replicate. This left a total of 99 plots for use in this paper. Heights of the center 49 planting positions were measured at ages 5 and 10. The d.b.h. of these same trees was measured at ages 10, 15, 20, and 25. At ages 15, 20, and 25, heights of at least 10 dominant or codominant trees were measured on each plot. Mean height of dominant and codominant trees at age 25 was used to represent site index of a plot. The d.b.h.'s were used to calculate basal area growth per tree from ages 20 to 25 for use as an index of individual tree growth.

Site Index Predictions

To find the optimum number of larger pines at an earlier age needed to predict site index at age 25, all measured trees in each plot were ranked by their height at the earlier age. Before ranking, a random value, less than 1 percent of the height, was added to the height of each pine. This transformation prevented ties in the ranked heights without affecting other statistics. The height of the largest pine in each plot at the earlier age was selected as the independent variable in a regression, having SI_{25} (site index at base age 25 years) as the dependent variable. Then the regression was rerun including the earlier-age heights of the two largest trees, three largest trees, and so on until the heights of all measured pines were included.

Basal Area Growth Predictions

To predict stand productivity at age 25, age-5 parameters were used in a general, mixed linear model. The model used was

$$BAG_{I-F} = f(HT_5, R_{HT5}, CI_{HT5}, LOC) + E,$$

where

BAG_{I-F} = annual basal area growth between initial and final age,

HT_5 = pine height at age 5,

R_{HT5} = rank of pine in plot based on heights at age 5,

CI_{HT5} = competition index based on height of pine and its neighbors,

LOC = location, and

E = unaccounted -or variation.

The competition index is based on Hegyi's index (Hegyi 1974), except that total pine height was used instead of diameter to compare the tree to its neighbors. In the CI calculations, the four nearest pines in the rows (distance=1.83 m) and the four pines in the diagonal (distance=2.59 m) were used. Because the pines in the border rows were not measured, only the 25 center pines were used to calculate the competition and subsequently used in the regression with stand productivity. Stepwise fits of the model were used to find the relative importance of each independent variable. The model was then refitted with all independent variables included in the order suggested by the stepwise fits. The same order was used for all growth periods tested. To model survival, a cubic equation was fitted between the height-based rank within a plot and survival at age 25.

RESULTS AND DISCUSSION

Site Index Predictions

The mean height of all live pines on each plot at age 5 is a poor predictor of SI_{25} , accounting for only 40 percent of the variation. At age 10, the mean height accounted for more of the variation, increasing to 69 percent. Age-15 height was not as useful as age-10 height when used in the model to predict site index, accounting for only 65 percent of the variation. Beginning at age 15, heights were measured only on sample trees, and this may account for the weakened relationship. Age-20 height, based on sample trees chosen by the same criteria used to select trees at age 15, was much more useful, accounting for 88 percent of the variation. The regression between all trees measured at age 25 and those identified as dominants and codominants had an r^2 of 0.95. The variation in site index between locations by heights at younger ages is similar to results for loblolly pine in the Florida Parishes of Louisiana (Wakeley 1971). In earlier reports (Ferree and others 1958, Wakeley and Marreo 1958), the 5-year-growth increment after pines had reached breast height was more closely related to site index than were total heights at young ages. However, in the present study, the height increment from age 5 to age 10 was not a better predictor than total height at age 10, accounting for 70 percent of the variation.

Ranking age-5 heights and using only taller trees did little to improve the relationship (fig. 1). The fit of the regression equation changed gradually from an r^2 of 0.45, when only the tallest tree was used, to an r^2 of 0.43 when the tallest one-half of all trees were used. The relationship was similar for other ages, with the amount of variation accounted for increasing with the age of the pines but not changing with the number of taller pines used. Thus, the prediction of future growth cannot be improved by selecting tallest or crop trees at early ages. As all pines must be measured to



Figure 1—Effect of percentage of largest pines included as independent variable on regression coefficient between age 5 heights and age 25 heights.

determine the tallest group, little is gained by attempting to designate dominants and codominants or crop trees for use in analyses and interpretations.

Detailed analysis of the changing ranks of pines with time can help explain why selecting larger pines at early ages does not improve the prediction of size at older ages. Ranks by ages are shown in figure 2 for two plots that show extremes in rank changes. Rankings of pines on plot 134-2 are relatively stable. For example, pine A is the tallest tree at age 5 and was still ranked number 5 by d.b.h.

at age 25. Pine B was ranked number 45 by height at age 5 and had changed by age 25 to ranking 32, or last, because other small pines died. By contrast, ranks on plot 139-3 changed dramatically with age. Pine C was in rank 41 by height at age 5, but had climbed in stature to having the 4th largest d.b.h. by age 25. Pine D, which was the tallest at age 5, ended in 23rd place by age 25. As the number of intersections of lines in the ranking diagrams indicates, most of the changes in rank seem to take place in the 5th through 10th years of the plantation. While mortality was concentrated in the lower ranks, the pines often moved from higher to lower ranks before dying.

Using a somewhat different analysis also aids in understanding the relationship between rank by height at age 5 and relative position in the stand at index age. Consider the population consisting of the tallest tree on each plot at age 5. At age 25, the mean ranking by diameter of this population was 5.1 (fig. 3A), with a range of 1 to 26. As the ranking at age 5 moves from large to small pines, the mean ranking at age 25 increases in a linear fashion. However, while the mean indicates a good relationship between rank at age 5 and rank at age 25, the large variation nullifies its utility as a predictor. Indeed, the population of pines ranked 36th at age 5 has nearly the same range of 4 to 39 as lower ranked trees (fig. 3A) even though the mean ranking by diameter has increased to 24. This wide range explains why selecting only a larger fraction of pines, based on age-5 heights, does not improve the predictability of SI_{25} (fig. 1). When ranks based on

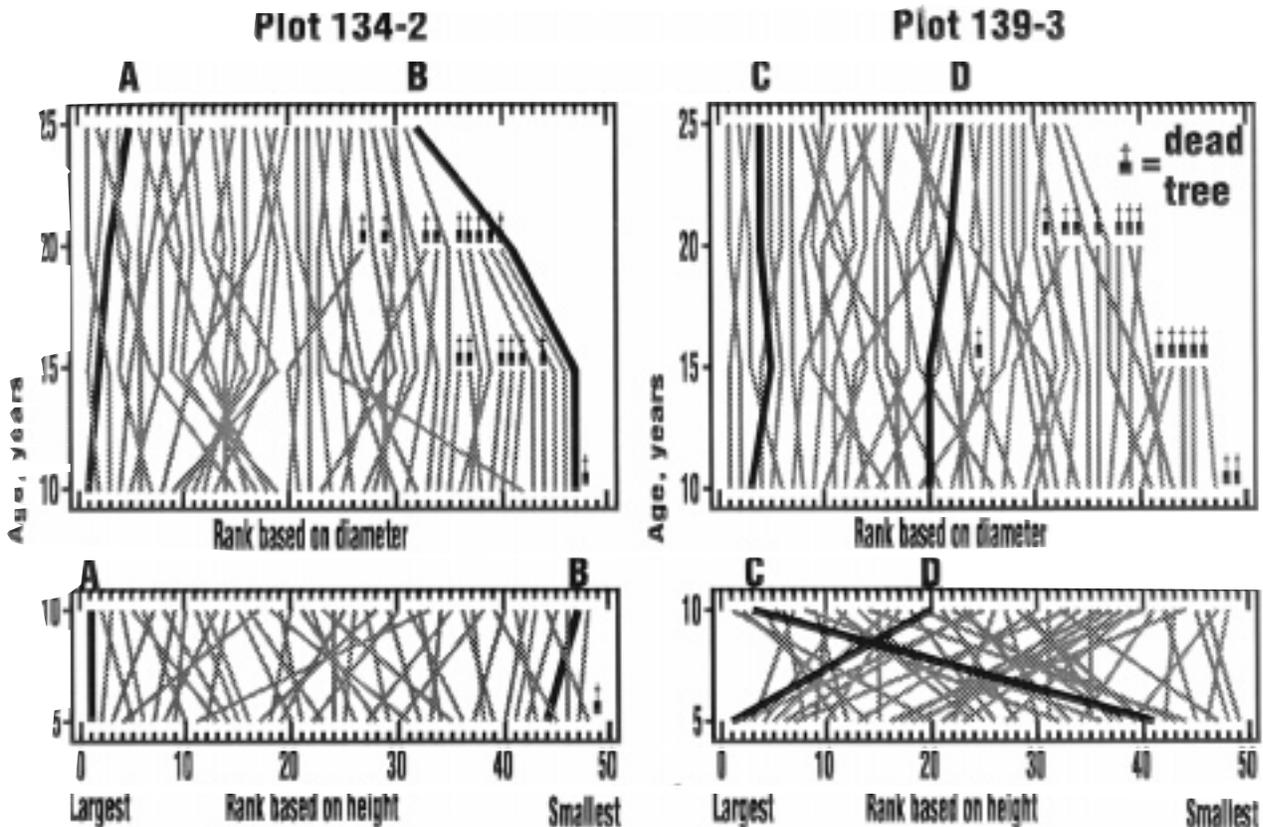


Figure 2—Pine ranks by heights and d.b.h. at different ages for two of the plots used in the analysis.

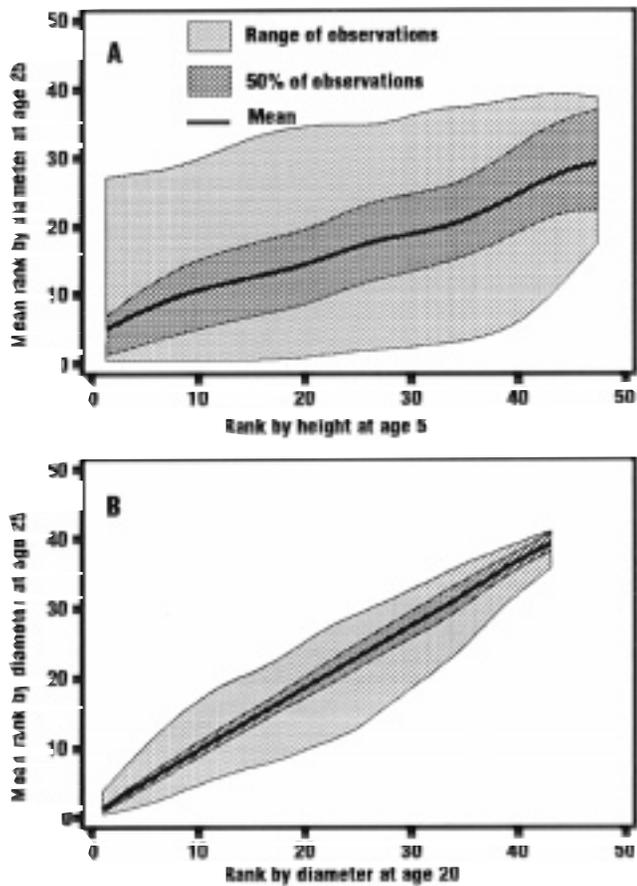


Figure 3—Relationship between rank by height at age 5 (A) and d.b.h. at age 20 (B) to mean rank by diameter at age 25.

diameter at age 20 are compared to ranks based on diameter at age 25, the mean ranking is remarkably similar to that at age 5 (fig. 3B). However, the range at all rankings at age 20 is much lower. This narrower range is expressed as a much higher r^2 in figure 1.

Basal Area Growth Predictions

Parameters for individual trees based on height at age 5 were of little value in predicting basal area growth of individual pines at later ages (table 1). The model accounted for about 35 percent of the variation in basal area growth between the ages of 10 and 15, but the model accounted for only about 20 percent for the age-20 to age-25 period. Height at age 5 accounted for less than 1 percent of the variation when included with the other variables in the model. Competition index, based on the height of a pine and its neighbors at age 5, was slightly more useful at the earlier ages, but by the age-20 to age-25 period, accounted for less than 1 percent of the variation. Ranking by height within plots was the only variable that was a better predictor at later ages than at earlier ones, accounting for 5.6 percent of the variation for the 10-15 age period and 9.9 percent of the variation for the 20-25 age period. Location was a good predictor for the 10-15 age period, but after age 15 it accounted for only 10 to 12 percent of the variation in basal area growth.

Table 1—Variation in basal area growth of loblolly pines of three ages accounted for by variables measured at stand age 5 years

Source	Sum of squares accounted for by variable at stand age		
	10-15	15-20	20-25
	----- Percent -----		
Height	0.54 ^a	0.03	0.07
Competition index	1.66	2.21	0.45
Rank in plot by height	5.55	10.78	9.91
Location	27.64	11.68	10.16
Unaccounted (error)	64.61	75.3	79.41

^a Percentage of total sum of squares (Type I).

Survival Prediction

Ranking by height at age 5 was an excellent predictor of individual tree survival (fig. 4). Of the pines that were the tallest on each plot at age 5, 95 percent were still surviving at age 25. In contrast, pines that were ranked near the bottom at age 5 had nearly all died by age 25.

CONCLUSIONS

Pine heights at age 5 accounted for about 40 percent of the variation in SI_{25} , indicating that projections based only on age-5 heights should be used with caution. Predictions or decisions based on age-5 results should be considered tentative and need to be reevaluated as later measurements become available. None of the parameters based on height at age 5 was independently useful in modeling individual pine basal area growth. Little is gained by attempting to

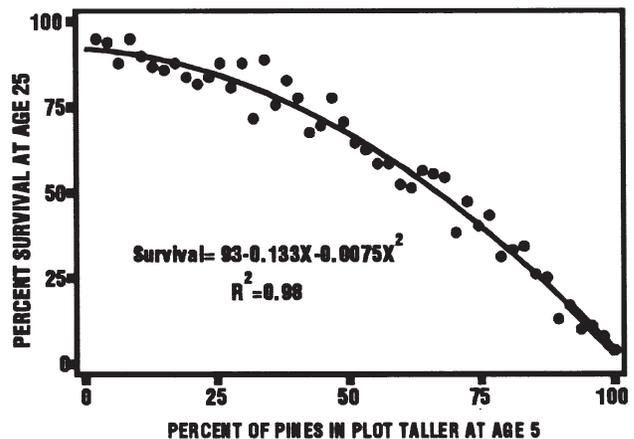


Figure 4—Relationship between rank of pines within each plot, based on height at age 5, and survival at age 25.

designate dominant and codominant or crop trees at age 5. A notable exception is that rank at age 5 was very useful in predicting survival of individual trees at age 25.

Predicting the site index or modeling stand development using early measurements probably requires more site information than is normally documented in research studies. Additional measurements need to be made to account for these factors, including competition, soil properties, past land management, and genetics. Competition at early ages may be an important factor in later stand size and structure. Pines on sites that have severe herbaceous competition may grow slowly in the first 5 to 10 years but grow more rapidly once the stand shades the competition (Haywood and Tiarks 1990). Soil properties may affect the rate of height growth by restricting root penetration or limiting water availability (Zahner 1962). The effects of soil properties may not be fully apparent until the stand has fully occupied the site. Past land management such as agricultural uses or prescribed fire may affect the amount and kind of woody competition and soil fertility. Some of the variation may be the result of differences in genotype, with some trees able to grow better after crown closure than before (Wakeley 1971).

We recommend that additional measurements be made beginning at age 5. These include diameters of the bole, both near the ground line and at breast height; the length of the crown; and a description of the amount and kind of competition. Studies should be located on sites that have uniform soils and have received common management in the past. More detailed studies should include crown diameter as well as a detailed measurement of the competition (Miller and others 1991). Unfortunately, the utility of these additional measurements will not be known until studies that have included these early measurements approach rotation age. Until then, studies testing new management practices should have a plot size large enough to allow measurement through rotation age.

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EFFECTS OF CLEARCUTTING ON STAND COMPOSITION AND STRUCTURE AFTER 17 YEARS OF REGROWTH IN A SOUTHERN APPALACHIAN STAND

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Abstract—The effect of clearcut regeneration with whole-tree yarding on plant composition and structure was examined after 17 years of regrowth. Shrub and tree strata were sampled 1 year prior to harvest and at 7 and 17 years after harvest. Species richness was highest 7 and 17 years after harvest in the shrub and tree strata, respectively. Invasion of pioneer (*Liriodendron tulipifera*, *Betula lenta*, and *Prunus serotina*) and regeneration of disturbance-dependent (*Pinus pungens*) species added to the species pool in both strata. Comparing species richness of preharvest to the 17th year data, species richness increased by one in the shrub stratum, while all preharvest species, plus an additional eight, were found in the tree stratum. The time for ingrowth accounts for the offset in the peak species richness between the two strata. Relative dominance (based upon basal area) for each species was not significantly different between the preharvest and 17 year data in either strata. Preharvest vertical stand structure was reflected in the 17 year data in both strata. In the tree stratum, stem density and basal area were high on better quality sites but low on poor sites. In the shrub stratum, stem density and basal area were high on poor quality sites but low on better sites. The faster growth rate on the better sites has resulted in stand closure which has limited light to the understory and caused density-induced mortality. After 17 years, clearcut regeneration has not significantly changed the composition and structure of forest stands; however, woody species diversity has increased.

INTRODUCTION

The Southern Appalachian Mountains are one of the two most biologically diverse areas of North America (Whittaker 1972). It is not uncommon to have 15 or more commercially important tree species on a given site (Smith 1994). The Ridge and Valley Physiographic Province contains most of the species and forest stand types of the region (Thompson 1992, Johnson 1992). The great diversity of this region is due to its unique topography, geology, and continental climatic conditions (Whittaker 1972).

Disturbance is another factor that has led to the high tree species diversity of the region. Since the turn of the century, major events, human and natural, have shaped the structure of the forest stands of the Southern Appalachians. These events include the nearly complete harvesting of the forests around the turn of the century, introduction of exotic pests [such as the gypsy moth (*Lymantria dispar*) and American chestnut blight (*Ednothia parasitica*)], and suppression of wildfires. The practice of clearcutting has caused significant controversy due partly to the aesthetic appearance of forests after harvesting (McGee 1970). More recently, questions have been raised on the effects that clearcutting has on the biodiversity (plant diversity) in forests (Gilliam and others 1995). Diversity is often tied to the sustainability of forests. Sustainability, in this case, means the maintenance of a productive, stable, and diverse forest system capable of providing desirable goods (i.e., food, wood, wildlife, recreation, etc.) in perpetuity.

Few studies have evaluated the effects of clearcut regeneration on forest stand structure and diversity in the Southern Appalachians (e.g., Beck and Hooper 1986, Elliot and Swank 1994). In most cases, these studies have been conducted in mesic, higher site-quality stands. Clearcutting

is a viable, biologically sound, and often used regeneration system on most sites for many reasons. Since the majority of the commercial tree species found in the Southern Appalachians are intolerant to intermediate of shade (Burns and Honkala 1990a, 1990b), clearcutting provides the forest floor conditions that are an ideal environment for them to regenerate. The majority (78 percent) of the Southern Appalachian mountain range is owned by private, nonindustrial landowners holding 400 acres or less (Smith 1992) and they tend to own land as an investment. Clearcut regeneration on these lands is the predominant regeneration technique since it is usually the most economical and profitable method (Cubbage and others 1993), and results in the most desirable new stand. The majority of stands in the Southern Appalachians are 70 to 100 years old, containing large and valuable trees that are of sufficient size for harvest depending on landowner objectives. Finally, they are old enough such that natural mortality is becoming an important factor in determining the future direction of the stand.

Little is known about the effects clearcut regeneration has on diversity with respect to the composition and structure of forest stands in the Southern Appalachians. Even less is known about this effect on the more typical stands (site index₅₀ of <75 for upland oak, base age 50) of this region. This study will report on the interim results (17 years) of a longer-term study that addresses the question of how clearcut regeneration affects woody plant species composition and structure after implementing clearcut regeneration silviculture on these typical stands.

STUDY AREA

The study area is located on the George Washington and Jefferson National Forest on Potts Mountain in Craig

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County, VA. The elevation is approximately 2,400 feet with stands located at midslope, with slopes ranging from 8 to 45 percent and having east to southwest aspects. Soils are classified as mesic, arenic or typic Hapludalts with a generally coarse texture of mainly siliceous mineralogy derived from residual or colluvial sandstone and/or shale parent material (Morin 1978).

Four forest types were delineated based on visual criteria of overstory and understory composition (McEvoy 1980). Stands were classified as one of the following: (1) cove hardwood overstory with no ericaceous understory, (2) mixed oak with a light ericaceous understory, (3) mixed oak-pine with moderate to heavy ericaceous understory, and (4) mixed pine with heavy ericaceous understory. For additional descriptions, see Ross and others (1983) and Blount and others (1987).

METHODS

Plot Establishment

In the original study, nine 0.4-acre permanent plots were distributed among the vegetation types in three harvested blocks. These plots were evaluated for site quality using site index (SI_{50} base age 50 for upland oak) (Olson 1959) and ranked from very poor ($SI_{50} = 37$) to moderately good ($SI_{50} = 71$). The vegetative composition of each of these types was subsequently found to be correlated to a soil moisture-site quality gradient (Meiners and others 1984). One of the plots was used as a control to detect any significant nonanthropogenic disturbances that occur over the life of the study. For the present study, five of the original plots were remeasured.

Between August 1978 and March 1979 the study area was clearcut using whole-tree harvesting and a cable yarding system. Cable yarding was used to minimize harvesting impacts on the steep slopes. All areas in which the plots were located were harvested during the dormant season except one plot which was completed in September 1978.

Data Collection

Five plots, one from each vegetation type and the control, were sampled in this study. Nested plots were used to sample the tree and shrub strata. A complete sampling (100 percent intensity) of sixteen 1,076 ft² tree subplots where all woody stems >16.4 feet in height were measured. Nested within the tree subplots were four 269 ft² shrub sub-subplots where all woody stems 3.3 to 16.4 feet in height were measured. In the shrub stratum, a rank set sampling scheme was used to measure 25 percent of the area in each plot. The original sampling period (preharvest) occurred between April of 1977 and March of 1978. Post-harvest sampling occurred in 1986 and 1996 (7th and 17th year after harvesting, respectively) during March and April of each year. [Refer to Blount and others (1987) for detailed description of stand regeneration between years 1977 and 1986.]

For the tree strata, measurements varied between the years. Preharvest measurements in the tree stratum

included recording the scientific name, diameter (to nearest 0.1 inch) at 4.9 feet above ground level, and total height (to nearest 0.1 foot) of each individual stem. For post-harvest measurements, the diameter was measured at 4.5 feet above ground level and only the height of every fifth tree of each species was measured. Measurements for the shrub stratum (in all measurement periods) for each individual included scientific name, diameter (to nearest 0.1 inch) at 5.9 inches aboveground level, and total height (to nearest 0.1 foot).

Methods of Analysis

To quantify the changes in plant species composition over time, species richness lists and relative dominance were compared among each of the three sampling periods. Relative dominance was based on basal area and was calculated for each species in each stratum. ANOVA was used to test for significant differences ($\alpha = 0.05$) in relative dominance for each species between the preharvest and 17th-year data. Basal area and stem density, plotted over time for each stratum, were used to examine any changes in the vertical structure of the forest stands.

RESULTS AND DISCUSSION

Species Composition

Species richness in the shrub stratum increased by the 7th year after harvest, then decreased to preharvest levels at 17 years (table 1). A total of 29 species were found over the time of the study period. The increase in species richness in the 7th year was mainly due to the invasion of pioneer or disturbance-dependent species. These included yellow-poplar (*Liriodendron tulipifera*), black birch (*Betula lenta*), black cherry (*Prunus serotina*), and Table mountain pine (*Pinus pungens*). From the 7th to 17th year, three species, serviceberry (*Amelanchier arborea*), black cherry, and northern red oak (*Quercus rubra*) were lost from the site while black birch, black locust (*Robinia pseudoacacia*), and striped maple (*Acer pensylvanicum*) grew out of the shrub stratum and into the tree stratum.

Table 1—Changes in woody species richness in the shrub stratum over three sampling periods in forest stands on Potts Mountain, Craig County, VA (0.4 acres total sample area)

Sampling periods		Initial total	Species	
From	To		Gained	Lost
Preharvest	7th yr	21	6	1
7th yr	17th yr	26	2	6
Preharvest	17th yr	21	4	3

No. of spp in 1996 = 22.

Total no. of spp from 1977 to 1996 = 29.

Species turnover in the shrub stratum between preharvest and 17th year remained low. Four species were added while three species were lost. Yellow-poplar, Table mountain pine, Virginia pine (*Pinus virginiana*) and sugar maple (*Acer saccharum*) were new while striped maple, blacklocust, and mockernut hickory (*Carya tomentosa*) were no longer found in the understory. Some of the species were previously on site but not represented in the shrub strata. For example, prior to harvest, Table mountain pine was found in the tree stratum but not in the shrub stratum. Additionally, species such as yellow-poplar were now found mainly on more mesic sites presumably from seed sources in adjacent stands. Species such as blacklocust were no longer found in the understory, probably because the light is too low for regeneration as some stands have developed or are approaching a closed canopy.

Species richness in the tree stratum remained virtually the same from preharvest to the 7th year then increased by the 17th year (table 2). From preharvest to the 7th year, there was a loss of four species and a gain of three. Three of the species that were lost [Table mountain pine, pitch pine (*P. rigida*), and black oak (*Q. velutina*)] tend to be found on the less productive sites and had not yet had time to grow into the tree strata. Two of the three species gained (yellow-poplar and black birch) were found in the more mesic stand areas. These pioneer species with their fast growth rate and in combination with increased light are able to reach the tree stratum quickly. By year 17, all preharvest species plus an additional eight, were found in the plots. Individuals, such as pitch pine and black oak, on the poorer quality sites have had enough time to grow into the tree strata. Additionally, pignut hickory (*Carya glabra*), mockernut hickory, and American elm (*Ulmus americana*), intermediate to later successional species, had grown into the tree strata.

The dominant species (expressed as relative basal area) in both the tree and shrub strata have not significantly changed over the study period though their rankings might have changed (figs. 1 and 2). There was one exception in the tree stratum in which the dominance of black oak was

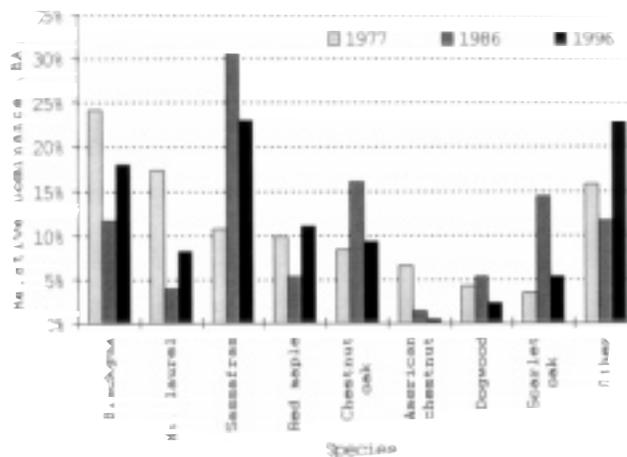


Figure 1—Dominant species (based on relative basal area) in the shrub stratum for all three sampling periods in forest stands on Potts Mountain, Craig County, VA (all site quality plots pooled).

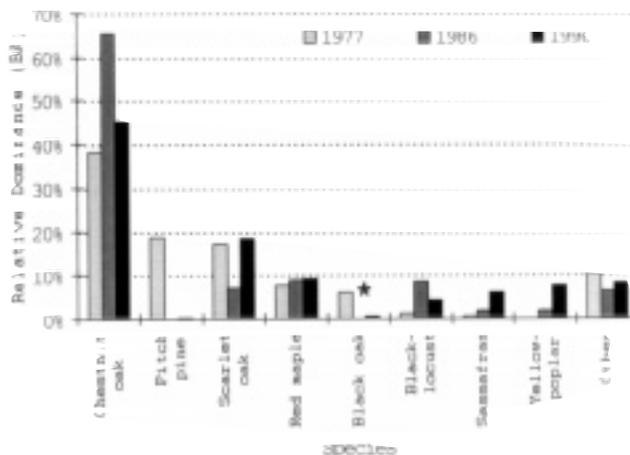


Figure 2—Dominant species (based on relative basal area) in the tree stratum for all three sampling periods in forest stands on Potts Mountain, Craig County, VA (all site quality plots pooled; * = significant difference between years 1977 and 1996 (alpha = .05)).

significantly different ($P < 0.02$) between the preharvest and 17th year. In the shrub stratum, blackgum (*Nyssa sylvatica*), mountain laurel (*Kalmia latifolia*), sassafras (*Sassafras albidum*), red maple (*Acer rubrum*), and chestnut oak (*Q. prinus*) have remained the dominant species. In the tree stratum, chestnut oak, scarlet oak (*Q. coccinea*), and red maple remained dominant species. The significant difference in black oak is probably a result of stand conditions affecting its regeneration ability. Sander and others (1984) found that black oak sprouting ability was greatly reduced for old trees on poor sites. Stump sprouts should have provided faster growth for black oaks to reach the tree stratum more rapidly.

There are some observations in changes in species dominance that are of interest to report. Table mountain

Table 2—Changes in woody species richness in the tree stratum over three sampling periods in forest stands on Potts Mountain, Craig County, VA (1.6 acres total sample area)

Sampling periods		Initial total	Species	
From	To		Gained	Lost
Preharvest	7th yr	13	3	4
7th yr	17th yr	12	9	0
Preharvest	17th yr	13	8	0

No. of spp in 1996 = 21.
Total no. of spp from 1977 to 1996 = 21.

pine and pitch pine are increasing in dominance in the shrub stratum on poor quality sites. This is probably as a result of the harvesting disturbance exposing mineral soil (the preferred regeneration medium). The apparent decline in the abundance of the pines is probably a result of the reduction in the fire frequency in the area (Ross and others 1982), an event which often exposes mineral soil. Yellow-poplar and sassafras, typically found on better quality sites, have increased in dominance. Yellow-poplar, on higher quality sites, should become a significant portion of the stands, since it is currently the dominant species along with red maple. This trend has also been observed in other studies (Beck and Hooper 1986, Elliot and Swank 1994). Sassafras, though still a component in the tree stratum, is reducing in dominance in the shrub stratum. As Blount and others (1987) predicted, sassafras should continue to decrease. American chestnut decreased, probably because of the confounding factor of chestnut blight.

Stand Structure

Since the study plots represented different vegetation types and, therefore, site qualities, the structure of each stand varied. In the shrub stratum, basal area peaked first in the higher site quality stands (fig. 3). By year 17, the shrub stratum basal area in the highest site-quality stand had returned to preharvest levels. Note that by year 7, the peak in basal area for the highest quality stand had probably already occurred. Stands with the highest productivity have the fastest in- and outgrowth from one stratum to the next. This would explain the sudden increase, then decrease, in understory basal area on these better sites. The same trend also occurred for stem density (fig. 4). By year 17, the lower quality sites, usually located on exposed ridgetops with shallow soils, may only achieve the equivalent of stand closure in the shrub stratum.

In the tree strata, 17 year basal areas, for all site qualities, reflected preharvest conditions (fig. 5). The high quality sites (preharvest basal area of 121 ft² per acre) had the

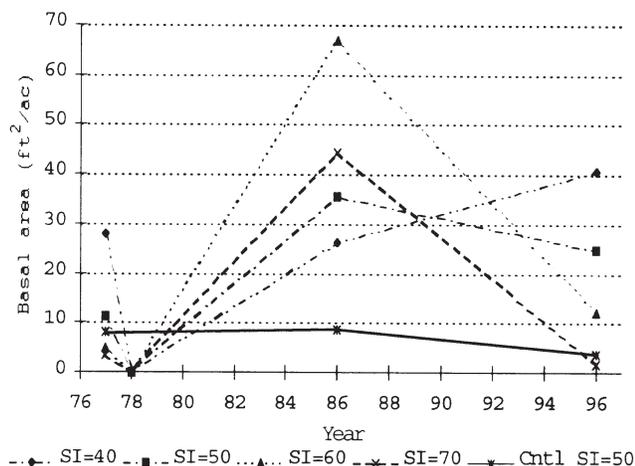


Figure 3—Changes in shrub stratum basal area over time in four different site quality forest stands on Potts Mountain, Craig County, VA [site quality based upon site index (ft) of upland oaks base age 50 (Olson 1959)].

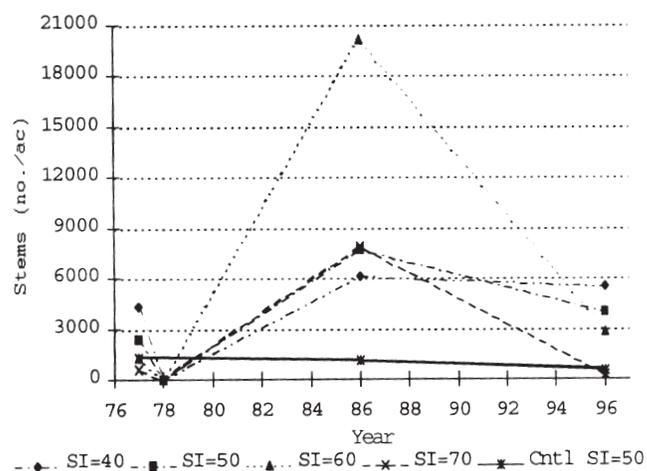


Figure 4—Changes in shrub stratum stem density over time in four different site quality forest stands on Potts Mountain, Craig County, VA [site quality based upon site index (ft) of upland oaks base age 50 (Olson 1959)].

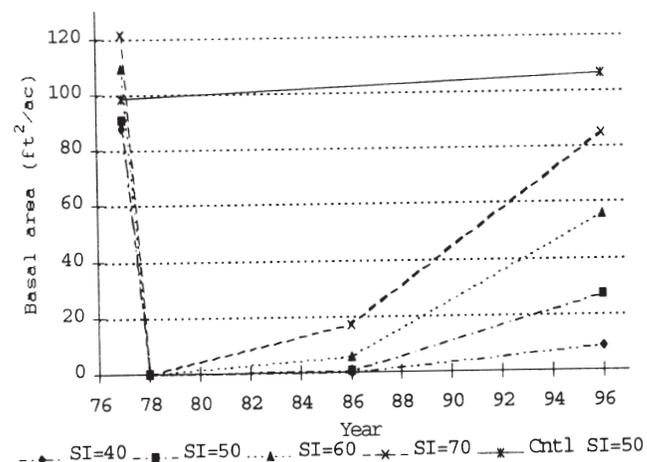


Figure 5—Changes in tree stratum basal area over time in four different site quality forest stands on Potts Mountain, Craig County, VA [site quality based upon site index (ft) of upland oaks base age 50 (Olson 1959)].

most basal area in the 7th and 17th years (16 and 85 ft² per acre, respectively). With respect to stem density, the higher quality sites had the highest density in both post-harvest samples (fig. 6). In year 17 though, the highest quality site did not have the most stems per acre. This is probably attributed to the stand achieving a closed canopy resulting in density-induced mortality. The high basal area is now being distributed among fewer individuals. The lower quality sites (preharvest basal area of 88 ft² per acre) still have not reached stand closure, therefore, they should continue to increase in basal area (7th and 17th year basal areas of 0 and 9 ft² per acre, respectively) and stem density for many years. The second highest quality site has probably reached stand closure and future sampling will show a decrease in stem density and a leveling off of basal area.

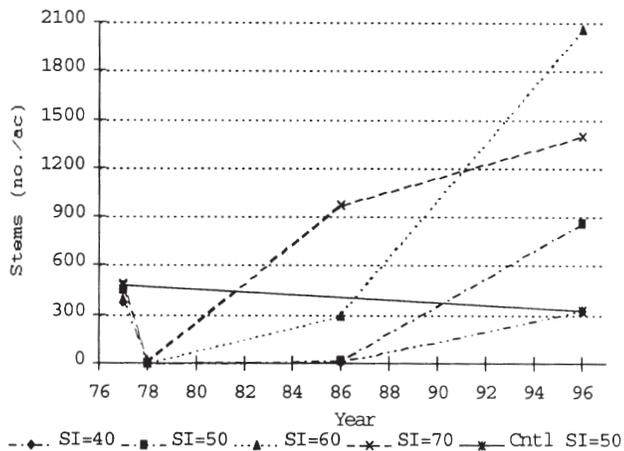


Figure 6—Changes in tree stratum stem density over time in four different site quality forest stands on Potts Mountain, Craig County, VA [site quality based upon site index (ft) of upland oaks base age 50 (Olson 1959)].

CONCLUSIONS

Among harvesting disturbances, clearcut regeneration can mimic natural disturbances that promote tree diversity in forest stands. In stands of the Southern Appalachians, clearcut regeneration has not significantly changed the composition and structure. Tree species richness has increased as a result of this disturbance in both the tree and shrub strata. The mesic stands have had the fastest stand development and have already achieved stand closure. Future stand compositions on these better sites are predicted to change. Oaks, once prominent on the better sites, are being replaced by yellow-poplar. Basal area and stem density are highest in the tree strata on the better sites. The poorer quality, drier sites, are still progressing to stand closure and have minimal changes in stand composition. They continue to be dominated by oaks and/or pines. The majority of the basal area and stem density is in the shrub stratum on these sites.

ACKNOWLEDGMENT

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BOTTOMLAND RED OAK STAND DEVELOPMENT WITH IMPLICATIONS FOR MANAGEMENT AND FUTURE RESEARCH

Brian R. Lockhart and John D. Hodges¹

Abstract—Stand development involves changes in stand structure over time. Knowledge of stand development patterns is crucial for effective forest management, especially southern bottomland hardwood forests. These forests contain more than 70 tree species, many of which have commercial value. In this paper, stand development patterns in bottomland red oaks (*Quercus* spp.), especially cherrybark oak (*Q. pagoda*), are reviewed although examples from other oak forest types are included. These studies were divided into three broad categories: even-aged mixed genus, even-aged single genus, and uneven-aged mixed genus. Categorization by genus was necessary because of the lack of knowledge about interspecific and intergenus competition within and between red oak species. Management implications based on these development patterns are discussed, including the importance of many of the non- or less-commercial species during stand development. Areas for future research are also suggested to increase the knowledge base on bottomland hardwood stand development.

INTRODUCTION

Stand development, or dynamics, involves changes in stand structure over time (Oliver and Larson 1996). These changes occur in both a horizontal sense, or distribution of stems, and a vertical sense, or distribution of tree heights, within a stand (Kittredge 1986). An understanding of how stands develop is required for the long-term management of forests, not only for timber production but also for wildlife, water, and recreation uses. The need for more stand development knowledge has led to an increased number of studies and even to recent acceptance of stand development as a discipline unto itself (Oliver and Larson 1996). This paper will review past stand development studies involving bottomland red oaks (*Quercus* spp.), especially cherrybark oak (*Q. pagoda*). Studies of northern red oak (*Q. rubra*) dynamics will also be included with results being inferred for cherrybark oak. Implications from these study results are presented as suggestions for more efficient management of bottomland red oak stands. Also, suggestions for future research in stand development of bottomland red oaks will be put forth in an effort to better understand the dynamics of bottomland hardwood forests.

STUDIES OF BOTTOMLAND RED OAK STAND DEVELOPMENT

Few studies have been conducted involving bottomland red oak stand development. Of these, only two have dealt with natural, even-aged, mixed genus stands typical of southern floodplains. Although few in number, these studies have provided valuable information into how bottomland red oak stands develop and they suggest that forest managers and landowners must reconsider their perceptions on oak stand management. These studies have been divided into three broad categories: even-aged mixed genus, even-aged single genus, and uneven-aged mixed genus stands.

Even-Aged Mixed Genus Stands

Only one detailed study of cherrybark oak stand development in natural, even-aged, mixed bottomland

hardwood stands has been conducted. In this study, Clatterbuck and Hodges (1988) used a combination of the chronosequence and the reconstruction techniques (see Oliver 1982 for a review of techniques in stand development research) in mixed cherrybark oak-sweetgum (*Liquidambar styraciflua*) stands growing on old-field sites. Their results depicted three patterns of cherrybark oak development depending upon the average spacing between a central (crop) cherrybark oak and adjacent sweetgum. The patterns were “restricted,” “unrestricted,” and “overtopped.”

In the restricted pattern of development, the spacing between a central cherrybark oak and neighboring sweetgum was approximately 6 to 18 feet. This spacing resulted in cherrybark oak height being initially lower than that of sweetgum. Then, 20-23 years after stand initiation, cherrybark oak overtopped sweetgum and emerged into the canopy overstory. Cherrybark oak emergence was the result of a decrease in the rate of sweetgum height growth along with an increase in the rate of cherrybark oak height growth. Clatterbuck (1985) suggested several reasons for this:

- (1) crown architecture—sweetgum exhibits an excurrent crown form while cherrybark oak exhibits a semi-excurrent crown form when competing with sweetgum but changes to a decurrent, spreading, form after emergence into the overstory;
- (2) crown abrasion—sweetgum twigs are smaller and more brittle at a given age as compared to cherrybark oak twigs, thus, during wind events, the terminal buds and twigs of sweetgum tend to break when scraped against twigs of neighboring cherrybark oak stems;
- (3) high initial sweetgum density—a high initial sweetgum density may delay intraspecific (within species) crown differentiation thus leading to stagnation (Johnson 1968); and
- (4) phenology—bud break in cherrybark oak, though occurring several days later than in adjacent

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sweetgum, occurs basipetally from the top of the crown while bud break in sweetgum occurs acropetally beginning at the base of the crown (Young 1980).

In the unrestricted pattern of development, the spacing between a central cherrybark oak and neighboring sweetgum was greater than 18 feet or the cherrybark oak was several years older than the sweetgum. Cherrybark oak, growing in these conditions, was essentially free to grow and thus experienced little crown competition from sweetgum following stand initiation. This condition is depicted in the height growth patterns in which cherrybark oak is always taller than adjacent sweetgum.

In the overtopped pattern of development, the spacing between a central cherrybark oak and neighboring sweetgum was less than 6 feet. Under these conditions, cherrybark oak stems were subordinate to adjacent sweetgum and stood little chance for survival (Clatterbuck 1985).

A comparison of the restricted and unrestricted patterns showed that the distance of neighboring sweetgum, i.e., the amount of interspecific (between species) competition, affected the carbon allocation patterns of cherrybark oak. With relatively small distances to neighboring sweetgum, more photosynthates were allocated to height growth as the oak tree competed for dominance: a survival mechanism. After emergence, or stratification, cherrybark oak height growth rate slowed but crown and basal, or diameter, growth increased. This change reflects the spreading habit of emergent oak crowns which increase leaf area thus leading to greater photosynthate production.

The spreading habit of oak crowns following stratification has also been noted by Kittredge (1988). This study, involving mixed stands of northern red oak, black birch (*Betula lenta*), and red maple (*Acer rubrum*) combined the reconstruction and chronosequence techniques. Stands chosen were approximately 40-60 years of age, a time in which northern red oak had recently stratified above birch and maple. The stands differed primarily in the density of oak present in the overstory. Since cherrybark oak and northern red oak may have similar patterns of development (Hodges and Janzen 1987), this study may shed light on cherrybark oak development as well.

Kittredge (1988) found that the number of trees within a 10-meter radius of a central northern red oak did not have a negative impact on 5-year basal area growth. On the other hand, the amount of neighboring oak basal area and number of oak trees had a significant negative effect on central oak basal area growth. Total basal area also had a negative effect on central oak basal area growth, but to a lesser extent than neighboring oak basal area. The major reason for this growth reduction involved intraspecific competition between oak crowns in the upper canopy following stratification. Crown expansion and subsequent basal area growth of individual oaks was greater in the presence of few oak competitors rather than many, a result of decreased intraspecific competition for growing space

sooner in the upper canopy. Kittredge (1986) suggested that this effect was due to:

- (1) wider crowns (lower oak density) have a greater surface area and are thus exposed to a higher quantity and quality of sunlight;
- (2) increased crown surface area in full sunlight produced a higher sun:shade foliage ratio and thus increased photosynthate production; and
- (3) smaller crowns (higher oak density) have an increased incidence of crown abrasion with stout twigs of neighboring oaks and possibly within individual crowns itself; therefore, an individual oak will allocate more photosynthate defensively to branch thickening at the expense of bole thickening.

Clatterbuck and Hodges (1988), Kittredge (1988), and Oliver (1976) have demonstrated the phenomenon of oak stratification through the chronosequence and reconstruction techniques. But only one study has given unequivocal evidence to bottomland red oak stratification through the use of the permanent plot technique.

Johnson and Krinard (1988) found that 28 years after stand initiation, bottomland red oak species [cherrybark oak, water oak (*Q. nigra*), and willow oak (*Q. phellos*)] began to emerge above sweetgum. They stated this situation was hardly predictable after 9 years when the overstory was composed primarily of sweetgum, river birch (*Betula nigra*), and American hornbeam (*Ostrya americana*). But, during normal stand development, the river birch began to die due to increasing competition, while the American hornbeam was relegated to an understory position. The authors postulated that red oak would exceed sweetgum in height within 30-35 years after stand initiation. The difference in time of stratification between this study and Clatterbuck and Hodges' (1988) study was probably due to the cutover sites utilized by Johnson and Krinard (1976, 1983, 1988) compared to the old-field sites utilized by Clatterbuck and Hodges. Similar results were reported by Bowling and Kellison (1983) in mixed stands of water oak, sweetgum, blackgum (*Nyssa sylvatica* var. *biflora*), and American hornbeam.

In summary, these studies suggest that cherrybark oak, and possibly water oak and willow oak, can reach a dominant or codominant position in even-aged, mixed genus bottomland hardwood stands. If given some direct overhead sunlight during the early years of stand development, bottomland red oaks will eventually surpass species such as river birch, American hornbeam, and sweetgum through intergenus competition. Once in the overstory, intraspecific (or intragenus) competition between oaks plays a major role in regulating growth and development of individual oak trees. But recent studies in other mixed-genus stands have shown that cherrybark oak (and probably other bottomland red oaks) will not stratify above species such as sycamore (*Platanus occidentalis*) (Clatterbuck and others 1987), loblolly pine (*Pinus taeda*) (Clatterbuck 1989), and possibly yellow-poplar (*Liriodendron tulipifera*) (O'Hara 1986) in stream and river

floodplains. Clearly, there is much still to learn about managing such complicated stands.

Even-Aged Single Genus Stands

The occurrence of natural, even-aged, single genus stands of bottomland red oak is believed to be the result of fortuitous events early in the life of the stand, such as fire and grazing, that eliminated competing species (Aust and others 1985). While pure stands of water oak and willow oak can be found on certain sites, pure stands of cherrybark oak occur much less frequently. Studies of how such stands develop provide useful insight into how bottomland red oaks interact when confronted with intraspecific (or intragenus) competition throughout their life. At present, only one study has been conducted involving stand development in single genus stands of bottomland red oaks, primarily cherrybark oak. Aust (1985) used the chronosequence technique to identify factors important in determining red oak structure.

Stratification in these pure stands differed from that of even-aged mixed genus stands. In single genus red oak stands, increased intraspecific competition among oaks may result in individual trees growing taller with lower live-crown percentages as compared to oaks from mixed stands. Such conditions could lead to increased lengths of branch-free boles through continual natural pruning by neighboring oak stems. Kittredge (1986) found that the height to the base of the main fork was positively related to the amount of northern red oak present in prestratified stands, which suggests that intraspecific competition early in a stand's development produced longer merchantable bole lengths. But similar results were not found by Aust (1985) in relatively pure bottomland red oak stands under either narrow or wide spacing between oak stems. Furthermore, early intraspecific competition between bottomland red oaks may increase stress within individual oaks stems, thereby increasing the probability of epicormic branching (Meadows 1995).

The major differences between single genus and mixed genus stands, in terms of growth and development of an individual oak stem, are (1) the intensity and onset of intraspecific competition between oaks and (2) the lack of interspecific competition in single genus stands. Aust (1985) concluded that pure oak stands had no major advantages or disadvantages over mixed-genus oak stands in terms of growth and yield. On the contrary, individual stems in mixed-genus stands will probably have larger diameters containing high quality wood. On a per-acre basis, fewer red oak stems of higher quality may be worth more than red oak stems grown in relatively pure stands. At present, this is speculative.

Uneven-Aged Mixed Genus Stands

In general, most research and management practices for bottomland red oak stands have assumed that stands are even-aged (Hodges 1987). Development of uneven-aged bottomland red oak stands has been largely neglected. This is due to several factors such as the relative scarcity of uneven-aged stands relative to even-aged ones, their

more complicated stand structure, and even the sense that uneven-aged silviculture in bottomland oaks is not viable (DeBell and others 1968, Hodges 1987).

However, Guldin and Parks (1989) conducted a stem analysis study in an uneven-aged cherrybark oak stand. The study consisted of 0.2-acre plots, each of which contained three distinct age classes of cherrybark oak. Their data suggested that cherrybark oak stratification occurred within canopy gaps created by the removal of large overstory trees. Two types of stratification were depicted. The first occurred within an age class, particularly the oldest age class, in which a single cherrybark oak seemed to dominate. The second type of stratification occurred between age classes. This was expected, given that younger stems start below older stems. Of particular interest were the developmental patterns between the tallest cherrybark oaks in each of the three plots. The dominant cherrybark oak in one plot was taller than neighboring stems early in its life. Therefore, the lack of more direct intraspecific competition as compared to the tallest cherrybark oak in the other plots may have led to its lesser height. This difference does not take into account the effects of the older, residual trees surrounding these gaps which should affect development within gaps.

Based on these results, Guldin and Parks (1989) stated that the development of cherrybark oak in gaps might be similar to the even-aged developmental dynamics as outlined by Clatterbuck and Hodges (1988). They also suggested that the absence of cherrybark oak in gaps created by single-tree and group selection cuts might be due to the lack of sufficient advanced regeneration at the time of harvest, rather than to the inability of existing advanced growth to develop.

MANAGEMENT IMPLICATIONS

Management of bottomland stands containing red oak is not complicated once stand development patterns have been recognized. Important considerations include the species composition and the ability of the forest manager to elucidate development patterns early in the stand development game, i.e., large-sapling to small-pole stage of development. Crop trees should be selected at this stage. The following suggestions for bottomland red oak management are based on neighboring species composition. These suggestions assume intermediate stand conditions; therefore, no consideration for regeneration is given. Also, biological maturity is assumed instead of economic maturity for rotation length due to an inherent bias for large sawtimber and benefits of large trees for wildlife.

Even-Aged Mixed Genus Stands

The key to managing bottomland red oak in even-aged mixed genus bottomland hardwood stands is the spacing between neighbors and the crop tree, beginning with the sapling to small-pole stage of development.

If neighboring trees are shade-tolerant species, such as ironwood, sugarberry (*Celtis laevigata*), elm (*Ulmus* spp.),

or less shade-tolerant species which contain small-diameter twigs, such as river birch or sweetgum, then bottomland red oaks (especially cherrybark oak) should stratify above these species. It is possible that stratification will occur in two stages. First, the bottomland red oaks would stratify above the more shade-tolerant species, most of which are relegated to a subordinate position when competing against less shade-tolerant species. Following a short period of time, bottomland red oaks would then emerge above the less shade-tolerant species and comprise the main canopy. Once the oaks have stratified above the other species, crown expansion would begin leading to increased diameter growth. The limiting factor on diameter growth would then depend on the onset of intraspecific competition between oak crowns in the upper canopy.

Under this development scenario, deadening or thinning the competing species before the oaks gain dominance would not be necessary since the oaks will gain dominance regardless (Kittredge 1986). Thinning these "trainer" species may lower merchantable height and bole quality of the oaks, thereby reducing their ultimate value. An assumption to this management option of basically doing nothing is that individual bottomland red oak stems attain some direct overhead sunlight throughout most of the early stages of their development.

If neighboring trees are less shade-tolerant than the oaks or equally shade-tolerant and have strong twigs and branches, such as yellow-poplar, sycamore, loblolly pine, and green ash (*Fraxinus pennsylvanica*), then it is less likely that bottomland red oaks can stratify above these species. Therefore, these species are the key competitors of bottomland red oaks. In the early stages of stand development it would be of benefit to the oaks if these key competitors were removed from the stand by deadening or thinning. Since ash crown dynamics seem to be similar to that of oaks (Kittredge 1986), and given the current stumpage value for premium ash, stems of this species may be considered as crop trees also.

If neighboring trees are other oak species, then spacing is especially critical. While the effects of other oak species competing with each other are not yet clear, it is reasonable to assume that intraspecific (or intragenus) competition will be more intense than intergenus competition. If neighboring oak trees are relatively close to crop trees, but not close enough to compete before stratification above other species, then intraspecific competition will begin soon after stratification. This competition for space in the upper canopy will decrease growth of the crown, and thus the bole. Therefore, two options exist to either avoid or alleviate early intraspecific competition following stratification. One is to deaden some of the future oak competitors early in the life of the stand. This option is heavily dependent upon the forest manager's ability to pick crop trees at a young age. A second option is to conduct a thinning operation following emergence of oak into the overstory. Such an operation is risky given the destructive nature of harvest operations on residual crop

trees, especially in relatively young, dense stands (Meadows 1993).

If neighboring oaks are so close as to cause intraspecific competition early in the life of the stand, then development will be similar to that of a pure oak stand. This possibility will be discussed in the section on development in single genus stands.

An optimum range of spacings between bottomland red oaks and its various neighboring species has yet to be determined except for cherrybark oak-sweetgum mixtures. Therefore, crop trees should be selected early in the development of a mixed stand and neighboring composition identified. Species such as yellow-poplar, sycamore, and loblolly pine should be deadened if they will compete directly with the oaks in the future. Deadening may consist of simple girdling. Subsequent sprouts of the hardwood species may not be able to compete starting underneath a larger sapling to small pole-sized stand. Many of the remaining species, i.e., shade-tolerants or small-twigged shade-intolerants, should be left. These species will enhance the development of bottomland red oaks by acting as "trainer" species.

Even-Aged Single Genus Stands

Stratification in relatively pure bottomland oak stands differs from that in mixed-genus stands, leading to red oak crowns codominating in the overstory since they usually will not emerge above one another. Management in relatively pure red oak stands also differs from that in mixed-genus stands. Due to a lack of intergenus competition, the forest manager will have to rely on intragenus competition to act as trainers of crop trees. This will result in smaller crowns and bole diameters, maybe even lower bole quality, in crop trees. Therefore, several thinning operations will be needed to promote good growth of crop trees. As previously mentioned, such operations increase the risk of damage to both boles and crowns of crop trees. Thinning may also increase the incidence for epicormic branching, further lowering bole quality (Stubbs 1986, Meadows 1995).

Development of relatively pure bottomland red oak stands seems to be the result of disturbance early in the life of the stand (Aust and others 1985), which should be avoided. Conventional wisdom suggests that it is better to have too much oak than none at all. But attempts should probably be made to control disturbances that promote the establishment and development of relatively pure red oak stands, in favor of retaining mixed-genus stands if high-quality saw logs are the desired product.

Uneven-Aged Mixed Genus Stands

Management of bottomland red oak in uneven-aged stands is hampered by the scarcity of information about development of such stands. At present, it may be best to view red oak development in the gaps of uneven-aged stands as development of small, even-aged mixtures. Guldin and Parks (1989) noted that the trees developing in a gap were of relatively the same age. Since plots were selected for cherrybark oak, the data also depicted intense

intraspecific competition within a gap. Furthermore, these oaks probably competed with trees of older age classes with larger crowns. Therefore, red oak crop trees have two conditions of intraspecific competition: within a gap and from around the gap. While intraspecific competition within a gap may produce crop trees with smaller crowns, the periodic removal of trees around the gap may allow crop trees to spread their crowns. Therefore, such trees may have more desirable characteristics as compared to those grown in even-aged single genus stands. Obviously, more information is needed on bottomland oak development in uneven-aged stands before more definite silvicultural prescriptions can be made.

FUTURE RESEARCH

There are many areas worthy of future research in stand development of southern bottomland red oaks. What follows is a list briefly describing several of these areas.

Stand Development

Future stand development studies should use combinations of the chronosequence and reconstruction techniques to better understand development patterns. Variations of these techniques could include point-chronosequence using stands of similar ages but with varying amounts of oak density (similar to Kittredge 1988). Another variation could include using gaps of different ages as a chronosequence within a stand for studying development in uneven-aged stands. These studies should include the following situations:

- (1) different sites within floodplains, such as ridges and fronts on small river bottoms, and within the loessial hills;
- (2) different species compositions such as green ash, hickory (*Carya* spp.), etc.; and
- (3) varying densities of bottomland red oak species.

Mixed-Species Plantations

At present, much effort is being expended on reforestation activities to convert former agriculture land to forest (Kennedy and Allen 1989). These activities involve establishing relatively pure bottomland oak stands or mixing several oak species. Based on reviews of previous stand development studies, such plantations may suffer in the long run as oak trees of lower bole quality may be produced (unless such stands are judiciously thinned). Therefore, stand development patterns need testing using a mixture of tree species with artificial regeneration techniques, such as planting and direct seeding. Such plantations could potentially produce more biomass compared to single-species plantations as different species occupy different canopy layers (Kelty 1992). One research effort studying mixed-species plantations and the effects of intraspecific and interspecific competition is underway using mixtures of Nuttall oak (*Q. nuttallii*), water oak, and green ash in an elaborate experimental design (Goelz 1995). Additional studies need to include other less-desirable species (from a timber standpoint) such as sweetgum, American hornbeam, and sugarberry to determine if such species can contribute significantly to

increased bole quality in addition to the added benefit of increased species diversity.

Crown Architecture

More study on the role of crown architecture in determining stand development patterns is warranted. Based on the previously discussed studies, the ability of a crop tree to compete successfully in the upper canopy depends on how well it can occupy physical growing space in the canopy. Future studies should include tests of relative twig and branch strength between species. Studies could also be conducted on crown expansion rates, foliage type (sun versus shade), and foliage distribution within a canopy.

Whole Tree Physiology

How well a crop tree competes ultimately depends on its ability to increase carbon allocation when more growing space becomes available. Therefore, information is needed on whole-tree leaf area and gas-exchange, i.e., net photosynthesis and transpiration. This information would not only increase knowledge on how bottomland red oaks grow but also provide insight into how they respond to competition from different species. Such a study has recently been completed with northern red oak, red maple, and black birch (Moser 1994).

Permanent Plots

While establishing more permanent plots to specifically study stand development would be desirable, the costs of such projects are probably prohibitive. Therefore, efforts should be made to expand data collection in existing growth and yield plots to encompass testing hypotheses about stand development. Furthermore, efforts should be made to retain permanent plot data when long-term studies are terminated. Such data may contain as yet unrealized benefits regarding stand development patterns.

CONCLUSIONS

An understanding of how bottomland red oak species develop is essential to making effective silvicultural recommendations for forest managers and landowners who own and manage bottomland hardwoods. The fact that oaks can exist for decades beneath other species and yet can ultimately dominate the stand reflects the dynamic and robust nature of the genus. Recommendations for intermediate silvicultural treatments must reflect these unique developmental dynamics.

The fact that oak developmental dynamics are so different from those of the southern pines is part of the challenge for forest managers and landowners in the South. For example, if pines lag behind other species, they generally cannot recover. Forest managers who are accustomed to thinning and releasing pines from competing species at young ages might be tempted to apply similar tactics in young mixed-species bottomland hardwood stands—and they might be making poor silvicultural decisions if they did.

The studies cited here epitomize how silvicultural recommendations must reflect the best scientific information available for the species being managed.

Although forest management ultimately depends on the objectives of the landowner, it is up to the forest manager to advise on how to best meet these objectives. Finally, knowledge of stand development patterns is rewarding in itself, in simply knowing how a stand grows and in being able to predict how it will look in the future.

ACKNOWLEDGMENT

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Footnote

To avoid repetition, intraspecific competition within a bottomland red oak species also refers to intragenus competition between bottomland red oak species unless otherwise noted.

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HARDWOOD PLANTATIONS AFTER 20 YEARS ON A MINOR STREAM BOTTOM IN SOUTHEAST ARKANSAS: SURVIVAL, GROWTH, AND VOLUNTEER INGROWTH

D.W. Carlson and J.C.G. Goelz¹

Abstract—Eight hardwood species were planted in May 1976 on a minor stream bottom at 8x8-foot and 12x12-foot spacings. Tree species planted include: green ash (*Fraxinus pennsylvanica* Marsh.), American sycamore (*Platanus occidentalis* L.), sweetgum (*Liquidambar styraciflua* L.), swamp chestnut oak (*Quercus michauxii* Nutt.), cherrybark oak (*Q. falcata* var. *pagodifolia* Ell.), water oak (*Q. nigra* L.), eastern cottonwood (*Populus deltoides* Bartr. ex Marsh), and Nuttall oak (*Q. nuttallii* Palmer). In both spacings, sycamore, sweetgum, and green ash had the best survival, diameter, and height by age 6. At age 20, sweetgum was the largest in d.b.h. and height, and cherrybark oak, water oak, and Nuttall oak were larger and taller than green ash and sycamore. Survival at age 20 was highest for sweetgum (96 percent) in both spacings and also high for green ash and water oak. For other species, survival was variable between spacings, with Nuttall oak having the lowest survival (42 percent) in the 8x8-foot spacing. Volunteer ingrowth into all plantations was primarily loblolly pine (*Pinus taeda* L.) and sweetgum. For either spacing, green ash plantations had the most volunteer ingrowth and water oak had the least. On average, the oak plantations had more sweetgum than pine volunteer ingrowth, and green ash, sycamore, and sweetgum plantations had more pine volunteers.

INTRODUCTION

Plantations of southern bottomland hardwoods have been established by public agencies, private nonindustrial landowners, and forest product companies. Many of these plantations have been established within the last 10 years. Research on plantation establishment has provided guidelines for establishment. However, information on growth and yield for midsouth oak plantations 20 years or older is limited (Krinard and Johnson 1988).

METHODS

The study site is located approximately 9 miles south of Monticello, AR. Prior to study initiation, the site consisted of 75 acres of mixed hardwood-pine forest that was harvested, cleared, root raked, and disked in the fall of 1975. The experimental design used was a randomized complete randomized block with four replications. Within each of the four replications, an 8x2 factorial design was used with two factors: species and spacing. Each study plot had 169 planting spots, arranged in a 13x13 row configuration. The soil type is Arkabutla, with pH between 4.9 and 5.3; the soil is poorly drained in some areas.

Eight tree species were planted at spacings of 8x8 foot and 12x12 foot. The eight species planted were: green ash (*Fraxinus pennsylvanica* Marsh.), American sycamore (*Platanus occidentalis* L.), sweetgum (*Liquidambar styraciflua* L.), swamp chestnut oak (*Quercus michauxii* Nutt.), cherrybark oak (*Q. falcata* var. *pagodifolia* Ell.), water oak (*Q. nigra* L.), eastern cottonwood (*Populus deltoides* Bartr. ex Marsh), and Nuttall oak (*Q. nuttallii* Palmer). The planting stock used was purchased from the State nursery. Planting started on May 10, 1976, and was completed by May 18th.

After planting, weed control was accomplished by disking five times for the first growing season. For years 2 and 3,

mowing was done monthly during the growing season. After year 3, mowing was done before each measurement until 1989. All mowing and disking was done in a single direction because the original study included plots with narrower spacings (2x8, 3x8) than the 8x8-foot spacing this paper is reporting. Shumard oak (*Q. shumardii* Buckl.) was originally planted but the nursery stock contained a mixture of different oaks. These plantations were cleared and Nuttall oak was planted after the first growing season. Therefore, the age of Nuttall oak is 1 year less than all other species. After the fifth growing season, plots containing cottonwood were dropped from the study. The species had good survival up to age 3, but by age 5 most trees were dead.

For the first 8 years, mean annual increment (MAI) was calculated. At age 8, the MAI in the 8x8-foot and 12x12-foot plantations had peaked for sweetgum, green ash, and sycamore. At this time, trees in every other diagonal row were cut and removed from the plots. The oak plantations have not been thinned. Therefore, comparisons will be made between thinned plots of green ash, sycamore, sweetgum, and unthinned plots of the oaks.

The study has been measured annually by taking measurements of survival, stump diameter [15 centimeters (.5 feet) above ground line], d.b.h., and total height. These measurements were done during the dormant season on each planting location within the interior 5x5 rows of each plot. Beginning in 1995, all volunteer ingrowth with a d.b.h. greater than 5 centimeters (2.0 inches) was recorded by species and measured for height and d.b.h. We will report survival, growth (height and diameter), and volunteer ingrowth at age 20.

Data were analyzed by ANOVA followed by Tukey's test for mean comparison ($\alpha = 0.05$). Survival percentages were transformed by arcsin (square root) prior to analysis.

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RESULTS AND DISCUSSION

Survival

Initial survival in the 8x8-foot spacing (fig. 1) was good for all species; at age 19, Nuttall oak had the lowest survival, (42 percent). One of four Nuttall plots had excellent survival (100 percent) but the other three had poor survival (less than 25 percent). However, in the 12x12-foot spacing (fig. 2), Nuttall oak was among the species having the highest survival (91 percent). Green ash, sycamore, and sweetgum were among the species having the highest survival for the 12x12-foot spacing; swamp chestnut oak had the lowest survival (62 percent). Mortality for all species generally occurred within the first 2 years with an occasional tree lost thereafter. However, after age 16, mortality of several stems had occurred in sycamore plots in both spacings and green ash in the 8x8-foot spacing (figs. 1 and 2).

Species, spacing, and species-by-spacing interaction terms are significant. Species having significantly lower survival rates than sweetgum in the 8x8-foot spacing (table 1) were cherrybark oak and Nuttall oak. In the 12x12-foot spacing (table 1), survival was significantly less for swamp chestnut oak when compared to sweetgum, green ash, and Nuttall oak. Only Nuttall oak had survival rates that differed significantly between spacings, but across species, survival tended to be lower for the 8x8-foot spacings.

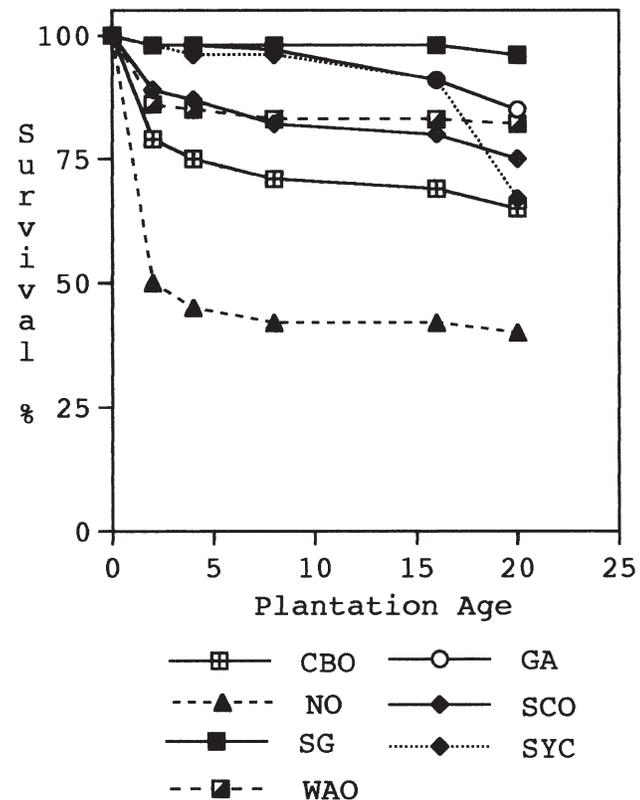


Figure 1—Average survival over time for the 8x8-foot spacing plantations. Species codes are: CBO = cherrybark oak; GA = green ash; NO = Nuttall oak; SCO = swamp chestnut oak; SG = sweetgum; SYC = American sycamore; WAO = water oak.

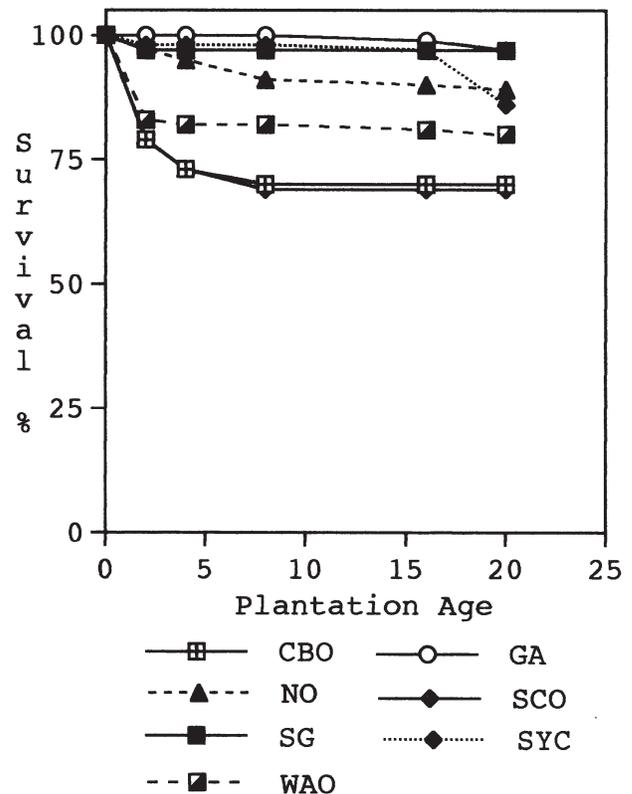


Figure 2—Average survival over time for the 12x12-foot spacing plantations. Species codes are: CBO = cherrybark oak; GA = green ash; NO = Nuttall oak; SCO = swamp chestnut oak; SG = sweetgum; SYC = American sycamore; WAO = water oak.

Table 1— Average survival, height, and diameter at age 20 for plantations on a minor stream bottom site in southeast Arkansas [letters signify results of Tukey's test for mean comparison (alpha = 0.05) and apply to both spacings for a given variable]

Species	Spacing					
	8x8	12x12	8x8	12x12	8x8	12x12
	Pct. survival		---Height (ft)---		----D.b.h. (in)----	
CBOa	65b	71ab	39b	47ab	4.6de	6.9ab
GA	85ab	97a	25c	36bc	3.1e	5.3bcd
NO	41b	91a	35bc	44ab	5.3bcd	5.9abcd
SCO	78ab	62b	28c	29c	3.8de	5.2bcd
SG	97a	96a	43b	52a	5.7bcd	8.1a
SYC	69ab	90ab	26c	35bc	3.0e	4.7cde
WAO	81ab	79ab	39b	45ab	4.4de	6.9abc

Species codes are: CBO = cherrybark oak; GA = green ash; NO = Nuttall oak; SCO = swamp chestnut oak; SG = sweetgum; SYC = American sycamore; WAO = water oak.

Mechanical damage from disking and mowing could have caused higher mortality on the 8x8-foot spacings. Some differences in initial survival may be a result of site variability. When the site was planted, there were places where mineral soil was exposed, mostly by erosion and clearing.

Diameter

Sweetgum, sycamore, and green ash were among the fastest growing species in diameter for both spacings (figs. 3 and 4) at age 6. At age 20, sweetgum was the largest species in both spacings, although not significantly different from cherrybark, Nuttall, and water oak. Swamp chestnut oak, sycamore, and green ash were among the smallest for both spacings. Average diameter appears to be decreasing for sycamore in the 8x8-foot spacing (fig. 3). This was caused by stem die-back below breast height followed by sprouting. Nuttall oak in the 8x8-foot spacing (fig. 3) was among the largest oak species. However, three replications had low survival, providing less tree competition and thus greater diameter growth. Water oak in both spacings was among the fastest growing species in diameter by age 10. At age 20, cherrybark oak diameter was slightly larger than water oak in the 8x8-foot spacing and equal in the 12x12-foot spacing (figs. 3 and 4) however, the difference is not significant (table 1). Diameter was greater in the 12x12-foot

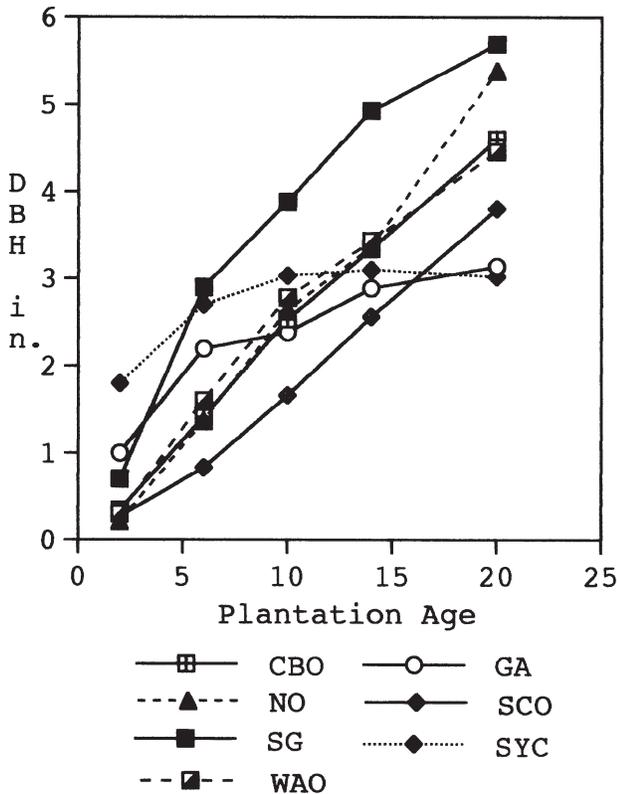


Figure 3—Average diameter over time for the 8x8-foot spacing plantations. Species codes are: CBO = cherrybark oak; GA = green ash; NO = Nuttall oak; SCO = swamp chestnut oak; SG = sweetgum; SYC = American sycamore; WAO = water oak.

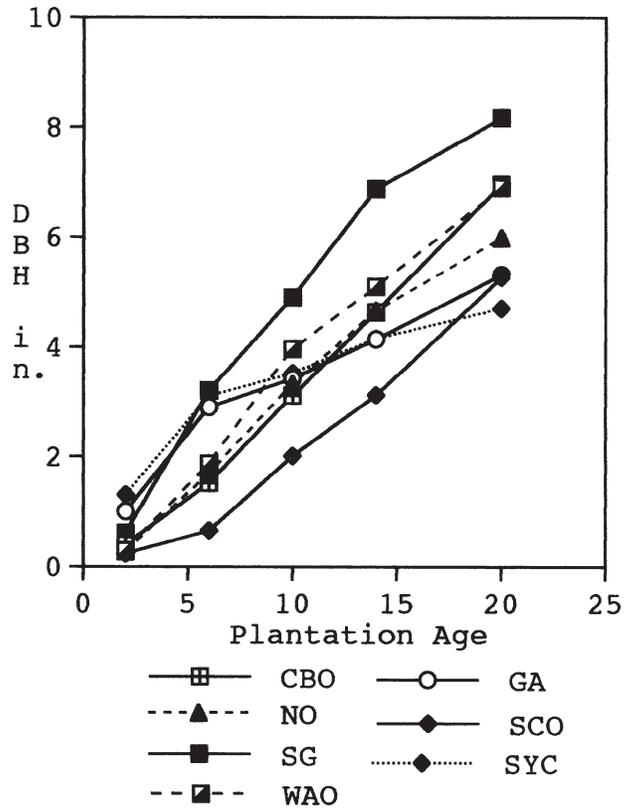


Figure 4—Average diameter over time for the 12x12-foot spacing plantations. Species codes are: CBO = cherrybark oak; GA = green ash; NO = Nuttall oak; SCO = swamp chestnut oak; SG = sweetgum; SYC = American sycamore; WAO = water oak.

spacing for all species although the difference was not significant for Nuttall oak, swamp chestnut oak, and sycamore. Results of the ANOVA and Tukey's test for diameters are displayed in table 1.

Height

Sweetgum, sycamore, and green ash were among the fastest growing species in height by age 6 (figs. 5 and 6). By age 20, sycamore and green ash average height increment had become negligible or negative. Water oak in both spacings had the fastest initial height growth among the tallest species. At age 20, cherrybark oak was slightly taller in the 12x12-foot spacing (fig. 6, table 1) however, the difference was not significant. In the first 2 years, average height for all species was greater in the 8x8-foot spacing. At age 20, average height was greater in the 12x12-foot spacing for all species, although this was only significant for sweetgum (table 1).

Possible reasons why green ash and sycamore were among the lowest in height and diameter growth at age 20 may be the result of low soil nutrients. Soil tests were taken and results revealed that nutrient availability for this site is poor and would be rated infertile for hardwoods; the levels were below or barely reaching acceptable levels for potassium, phosphorus, and calcium (Kennedy and others

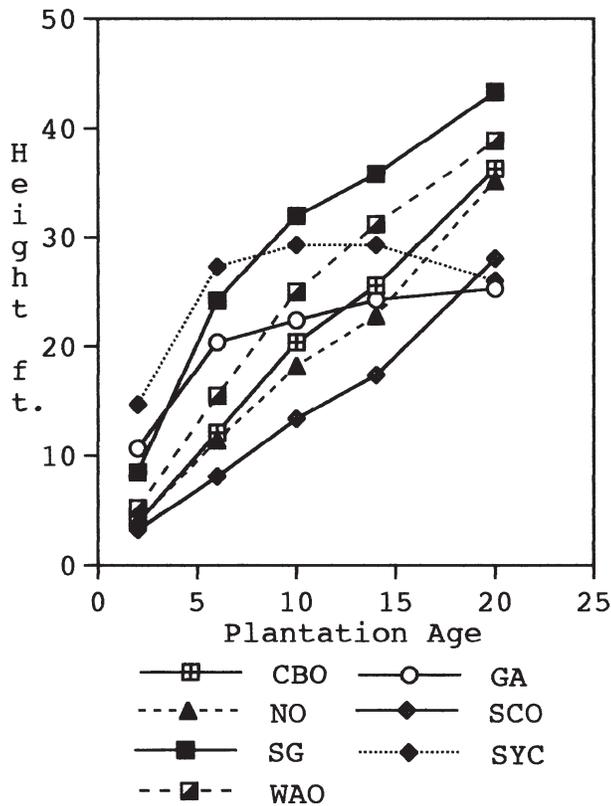


Figure 5—Average height over time for the 8x8-foot spacing plantations. Species codes are: CBO = cherrybark oak; GA = green ash; NO = Nuttall oak; SCO = swamp chestnut oak; SG = sweetgum; SYC = American sycamore; WAO = water oak.

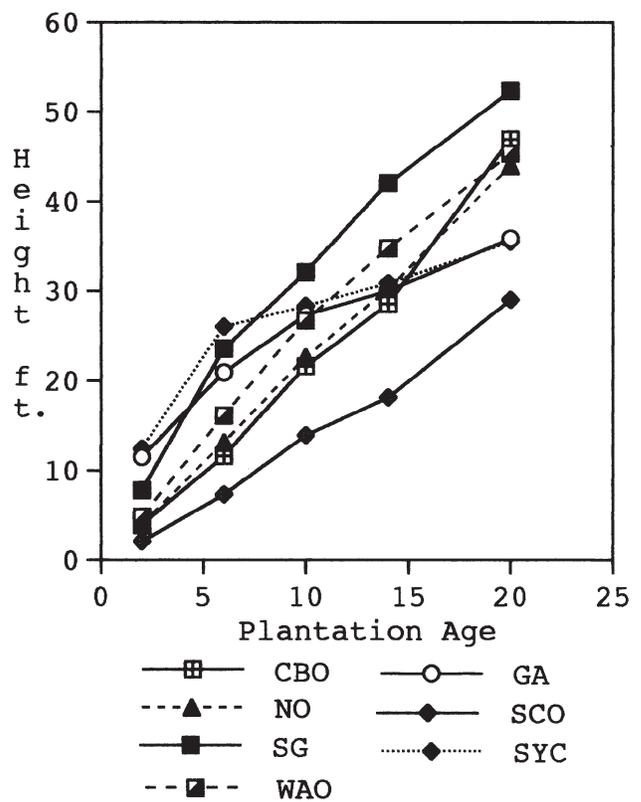


Figure 6—Average height over time for the 12x12-foot spacing plantations. Species codes are: CBO = cherrybark oak; GA = green ash; NO = Nuttall oak; SCO = swamp chestnut oak; SG = sweetgum; SYC = American sycamore; WAO = water oak.

1987). Green ash has shown good survival on acidic sites (soil pH 5.4 or below), but low annual height growth rates of 1 foot have been reported (Kennedy 1991). Sycamore may have low productivity on specific microsites within the Arkabutla soil series when the soil physical condition, nutrient availability, moisture availability, and soil aeration are poor (Briscoe 1969).

Volunteer Ingrowth

Most volunteer ingrowth occurred within the row due to disking and mowing being done in a single direction. Volunteers are primarily loblolly pine (*Pinus taeda* L.) and sweetgum. In both spacings, the green ash plots had the greatest basal area of pine volunteers (table 2); water oak plots were among the lowest for pine and hardwood volunteers. Significant differences in volunteers were found among species but not spacings or species-by-spacing interaction. Generally, plots of species that survived and grew well had less volunteer ingrowth than plots where survival or growth was low. When the basal area of planted trees and basal area of volunteers were summed, there was no significant difference in total basal area between spacings or among species (table 2).

Table 2—Volunteer ingrowth in basal area per acre and total basal area of planted and volunteer trees at age 20 in plantations on a minor stream bottom site in southeast Arkansas [letters signify results of Tukey's test for mean comparison (alpha = 0.05) and apply to both spacings for a given variable]

Species	Basal area		
	Pine	Hardwood	Total
CBOa	5.3b	7.7ab	75.2a
GA	51.2a	12.3ab	89.5a
NO	13.5b	6.3a	69.1a
SCO	17.8b	14.1a	75.7a
SG	10.5b	0.003b	77.1a
SYC	22.8b	16.1a	61.7a
WAO	0.1b	3.3ab	72.3a

Species codes are: CBO = cherrybark oak; GA = green ash; NO = Nuttall oak; SCO = swamp chestnut oak; SG = sweetgum; SYC = American sycamore; WAO = water oak.

CONCLUSIONS

Green ash and sycamore initially had good survival and grew well; however, growth was minimal over the last 10 years and mortality was increasing. Volunteer ingrowth was greatest in the green ash plots and lowest in the water oak plots. When the volunteer basal area was added to the planted basal area, there was no significant difference between spacings or among species. This may indicate that given sufficient influx of volunteers, the total basal area at age 20 was determined by the capacity of the site. We expect that in the future, total basal area for plantations of different species will differ due to natural stand dynamics. Even though soil nutrient availability was low, growth of cherrybark oak, water oak, and Nuttall oak was good. At age 20, sweetgum, cherrybark oak, and water oak were the best species, based on survival, height, and diameter.

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ABOVEGROUND BIOMASS AND LEAF AREA DYNAMICS OF INTENSIVELY MANAGED, 3-YEAR-OLD SWEETGUM COPPICE

Glenn W. Gladders and Klaus Steinbeck¹

Abstract—Sweetgum coppiced in April of 1994 has been growing at a 1.2x2.4-m spacing on an intensively managed plantation in Tattnall County, Georgia. Four treatments consisting of two levels of fertilization (570 and 1,140 kg of 20-10-10 per hectare per year plus micronutrients) and two levels of moisture (natural rainfall and rainfall + 150 cm per growing season through drip irrigation) are being applied annually. The partitioning of aboveground biomass among foliage, bark, stem wood, and branch wood was determined through destructive sampling of approximately 150 trees. Regression equations predicting percent biomass of each component from diameter at breast height were developed. Additionally, the cumulative area of fallen leaves was estimated through monthly collections of leaf litter from 1x1-m leaf traps. No significant differences between treatment means were found for any measured variables after 3 years. Dominant trees averaged 5.4 m in height three growing seasons after coppicing. Average dry weight of aboveground biomass was 37.2 t/ha, representing a mean annual increment of 12.4 t/ha/year. At the stand level, about 55 percent of that biomass was stem wood, and the remaining 45 percent was divided equally among branch wood, bark, and foliage. Cumulative leaf area index of fallen leaves for the entire growing season averaged 7.2 for all treatments.

INTRODUCTION

Demand for hardwood fiber has increased rapidly due to the increased manufacture of coated board and fine papers (Cubbage and others 1995, Howell and Hartsell 1995). Much of the existing hardwood supply is found on bottomland sites, where wet winters restrict logging operations. Mills must be supplied year-round and this has led to interest in growing hardwood plantations on upland sites which can serve as emergency reserves during supply crises. In the South, this interest centers on the Coastal Plains because of the high pulp mill capacity located in this geographical area.

Uplands usually are not the best sites for hardwoods. Cultural treatments, especially fertilization and weed control, are needed for their satisfactory growth (Wittwer and others 1978). The study reported here is part of a larger experiment in which sweetgum (*Liquidambar styraciflua*) and sycamore (*Platanus occidentalis*) coppice are being grown on an upland under cultural treatments designed to supply optimal nutrition and soil moisture. The study reported here was designed to determine the total, aboveground biomass production of sweetgum grown on an upland site for 3 years after coppicing. Allocation to stem and branch wood, stem and branch bark, and foliage, as well as changes in foliar mass during the growing season, were estimated.

MATERIALS AND METHODS

Site Description

The study site is located in the Middle Coastal Plain in Tattnall County, GA. Topography is flat with some minor local variation. Average rainfall is about 115 cm per year. Previous to this study, the site was an agricultural field and Christmas tree plantation. Soils are in the Leefield and Fuquay series of Arenic and Plinthaquic Paleudults. These soils typically have a 60-cm thick loamy sand A horizon and a B horizon consisting of sandy clay loam and sandy loam.

Both soils are acid throughout, with pH between 4.5 and 5.0. Site index (base age 50) for loblolly pine is 25.3 m. Organic matter content and inherent soil fertility are low, but fertilization of these soils can make them suitable for hardwood plantations.

Plant Material

In 1978, bare-rooted 1-0 nursery-run sweetgum seedlings were purchased from the Georgia Forestry Commission and planted at a 1.2x2.4-m spacing. In April 1994, all of these trees were clearcut, allowing regeneration through stump sprouting. In June 1994, all plots received 1,820 kg of 10-10-10 per hectare to stimulate rapid growth of the new sprouts. Early in the second season of growth, Roundup was applied to control competing vegetation. Canopy closure was achieved later that year, so no further herbicide applications were needed.

Treatments

Two irrigations and two fertility levels were used in this study. The field was divided in halves and one side received natural rainfall only, the other rainfall plus 150 cm of water by drip irrigation, during each growing season. Within each irrigation treatment were four plots, about 1/4 hectare in size (48.8x54.9 m). Each of these plots was split to receive estimated optimum nutrition (570 kg 20-10-10 and 0.2 kg Cu, 0.3 kg Mn, and 1.1 kg Zn per hectare per year) on half of each plot and double these amounts on the other half. Granular fertilizer was broadcast on the nonirrigated plots at the beginning of each growing season. The irrigated plots received their fertilizer in liquid form injected into the irrigation water throughout the growing season. The entire field was also treated with 2.5 tonnes of calcitic limestone and 28 kg of elemental magnesium broadcast per hectare in 1996.

Data Collection

Biomass study—In order to develop regression equations relating diameter at breast height (d.b.h.) to biomass of

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stem and branch wood, foliage, and bark, whole trees were harvested in June and again in August of 1996. Approximately 75 trees were cut on each of these two collection dates, equally distributed over five 1-cm diameter classes ranging from 2 to 6 cm. Equal numbers of trees were cut in irrigated and nonirrigated plots. Because no morphological differences due to fertility level were expected, trees were cut from border rows between fertility treatments. Sprouts were severed at ground level with shears or chainsaw, placed on a trailer, and brought to University of Georgia facilities in Athens for separation into component parts.

Subsampling was necessary in the field to ensure that an accurate estimate of leaf mass was obtained, as a large percentage of leaves were stripped from branches during transport from the site. Two of the 5 trees in each diameter class, or 30 trees on each date, were subsampled. Every third branch was removed and all branches from each subsampled tree were sealed in a plastic bag for transport. Subsamples were stored at 5 °C until leaves and branches could be separated. Leaves and branches were dried separately in an oven at 60 °C to constant weight. Dry weights of branches and foliage were multiplied by three to obtain an estimate of whole-tree dry branch and foliage biomass. SAS software was used to develop a regression equation relating foliage biomass to d.b.h.

Remaining trees were separated into stems and branches. Stem bark weight was estimated by removing bark from a subsample of 10-cm sections cut from each stem at 1-m intervals and drying bark and wood separately. Simple ratios were then used to estimate stem bark mass. For branch bark, 25 branches representing the entire range of branch diameters were stripped completely of bark, and a regression equation was derived to estimate branch bark and branch wood biomass from branch diameter. The diameters of all branches on 40 trees were then measured, and a final regression equation was derived to predict the mass of all branch wood and all branch bark from tree d.b.h.

In January 1997, diameters and heights were measured. Biomass of each component was estimated for each measured sprout using regression equations. Per-hectare estimates were then obtained through multiplication with the appropriate conversion factor.

Leaf area study—In order to estimate the mass of abscised leaves, 48 1x1-m litter traps were installed in June of 1996. Three traps were placed within each fertility/irrigation treatment plot. Approximately every 4 weeks, the contents of all traps were collected, dried, and weighed.

A subsample of leaves from the June whole-tree harvest date was used to develop a regression equation to estimate fresh leaf area from dry leaf weight. Leaves from various crown positions in all treatments were measured for leaf area on a Li-Cor meter. These leaves were then dried to constant weight and an equation was developed.

RESULTS

No significant differences were found between treatment means for any of the measured variables after three growing seasons (table 1). No significant interaction effect was found on any variable for the different fertilization/irrigation treatment combinations.

After three growing seasons, aboveground biomass averaged 37.2 t/ha (table 2). This represents an increase of 14.6 t/ha during year 3, and corresponds to a mean annual increment of 12.4 t/ha/year. Height of the dominant trees for all treatments averaged 5.4 m, an increase of 1.2 m during the third growing season (table 1). Aboveground biomass was produced at an increasing rate.

As d.b.h. increases, the proportions of stem wood and branch wood increase, while those of bark and foliage decrease (fig. 1). Stem wood is the largest component of a given sprout across the entire range of diameters observed, generally comprising over one-half of a sprout's dry weight. These data show how aboveground allocation changes with growth for a single sprout rather than for the stand as a whole.

At the stand level, the proportion of total biomass found in each component part depends on sprout diameter distribution. After three growing seasons, an average of 55 percent of total aboveground biomass was stem wood. The remaining 45 percent was divided approximately equally among branch wood, bark, and foliage (fig. 2). Of the 37.2 t/ha aboveground biomass, nearly 85 percent, or about 31.8 t/ha, is wood and bark.

Table 1—P-values for mean total biomass and height after three growing seasons, all treatments

Term	Total biomass	Height
Model	0.63	0.79
Fertilization	0.53	0.56
Irrigation	0.26	0.74
Interaction	0.99	0.45

Table 2—Mean height and aboveground standing biomass after two and three growing seasons, all treatments

No. of growing seasons	Height	Yield
	<i>m</i>	<i>T/ha</i>
2	4.2	5.4
3	22.6	37.2

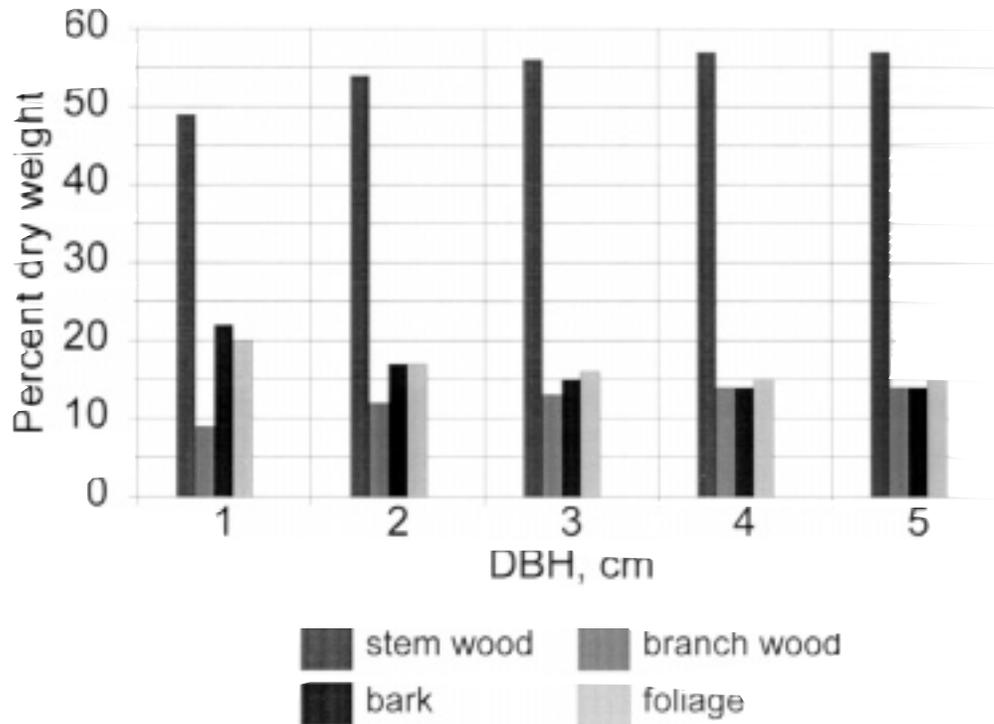


Figure 1—Accumulation of biomass in stem, bark, branch, and foliage for trees in five diameter-at-breast-height classes.

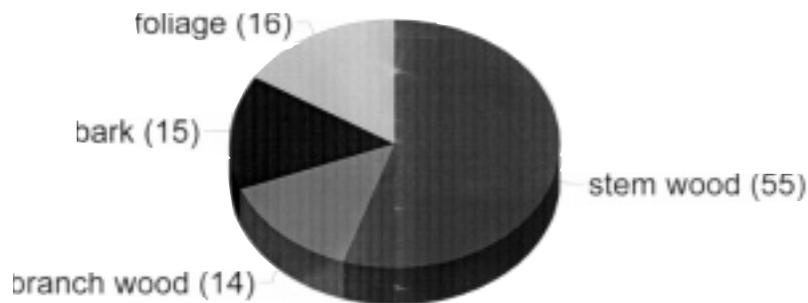


Figure 2—Average percent aboveground dry matter accumulation by tissue component 3 years after coppicing.

The estimated cumulative leaf area index of the leaves caught in the litter traps at the end of the third growing season was about 7.2 (fig. 3). Day 0 in figure 3 represents June 30, when the litter traps were installed. Leaves fell most rapidly during November and December, although senescence occurred to some extent year-round in these plots. Decagon's linear ceptometer device, AccuPAR, gave an estimated leaf area index (LAI) of 4.0 in late July of the third growing season.

DISCUSSION

Smith and others (1975) estimated that hardwoods growing in major river bottomlands in the South produce an average of about 5 tons/ha/year aboveground woody biomass. The sweetgum trees in the present study are producing about 12 tons/ha/year on a fertilized and irrigated upland site. The

difference is due, in part, to the cultural treatments. Furthermore, coppice regeneration grows on an established root system with its carbohydrate reserves and immediate access to soil resources.

The lack of treatment effects is not particularly surprising. All 3 years after coppicing were relatively wet, so water has not been limiting even in the nonirrigated plots. The optimum fertilization level is rather high; the twice-optimum level was included to ensure that the major nutrients were not limiting growth.

It might be suggested that these sweetgum trees have attained their maximum growth rates. However, numerous studies (Cannell 1989, Cannell and Smith 1980, Stott and others 1982) involving intensively managed hardwood

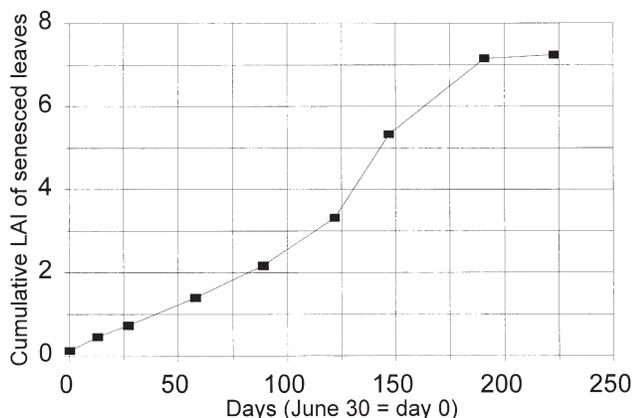


Figure 3—Cumulative leaf area index of fallen leaves during the third growing season.

species have shown production rates in the range of 15-20 t/ha/year in temperate zones of North America and Europe. Over 20 t/ha/year were produced with irrigation and N fertilization in Sweden using *Salix* (Cannell 1989), not typically considered an exceptionally fast grower. It seems reasonable to conclude that the sweetgum used in this study should be able to produce more than the current 12 t/ha/year.

Some other limiting factor is probably present at the study site. Nutrient analyses are being carried out on plant tissues at this time. Low supply of a micronutrient is a possible limiting factor, although any of a number of factors may be responsible for limiting growth.

Regression equations show that as d.b.h. increases, the proportion of stem and branch wood increases while that of foliage and bark decreases (fig. 1). A recent study (Wang and others 1996) showed similar results in *Betula papyrifera*, and these trends are applicable to tree growth in general. On a cross-sectional basis, stems and branches will increase in area more rapidly than in circumference, so the proportion of bark will decrease as trees grow. The foliage of small seedlings consists of a few large leaves but may represent over 50 percent of its aboveground biomass. Over time, stems and branches will accumulate biomass at rates exceeding the increase in leaf biomass. Eventually, mutual shading limits further increases in leaf biomass, especially after canopy closure is reached.

About 85 percent of aboveground biomass after three growing seasons is wood and bark usable for pulp, similar to results from other studies using hardwoods grown for pulp (Hook and others 1990). Within the aboveground portion, any increase in proportion of woody biomass would have to come from a decrease in allocation to leaves. Leaf area is strongly correlated with growth rate, so a decrease in allocation to leaves would be undesirable.

The large difference between instantaneous LAI (4.0) and total LAI of fallen leaves for the entire growing season (7.2) indicates a high within-year leaf turnover rate. Fertilization apparently causes increases in rates of both leaf production and leaf turnover. The optimum LAI for dry matter production is usually about 5.0 (Doley 1984), further evidence that these trees are capable of producing biomass at rates higher than the current 12 t/ha/year.

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STAND DENSITY EFFECTS ON BIOMASS ALLOCATION PATTERNS AND SUBSEQUENT SOIL NITROGEN DEMAND

Christopher A. Dicus and Thomas J. Dean¹

Abstract—Growth and yield data from a loblolly pine plantation in southeastern Louisiana were obtained yearly from 1993 to 1996 on numbered trees within two stands initially planted on a 1.22- by 1.22-meter spacing, and two stands planted on a 2.44- by 2.44-meter spacing. Using allometric equations derived from a 1994 on-site destructive harvest, cited nitrogen concentrations of various tree tissues, and accounting for foliar nitrogen retranslocation, stand growth and soil nitrogen demands were determined.

Results showed that production of all aboveground tissues increased as stand density index (SDI) increased. Annual soil nitrogen demand increased with SDI primarily as a result of an increase in nitrogen-rich foliage on the denser sites. Belowground production, as estimated from minirhizotron censuses, also increased as SDI and aboveground nitrogen demands increased. More fine-root production per unit aboveground nitrogen demand was observed on less fertile plots. Stemwood production per unit leaf biomass decreased with increasing SDI, and is assumed to be the result of a greater percentage of total net primary production being partitioned to fine-root production in the denser plots.

The results of this study suggest that the density of forest stands may influence nutrient demands from the soil and subsequent belowground productivity through differential aboveground biomass allocation patterns and tissue nitrogen concentrations.

INTRODUCTION

The underlying mechanisms of plant biomass partitioning are of great importance to the study of forest productivity. As gains are made in understanding the fundamental principles of photosynthate allocation to various tree components, the potential exists to manipulate forest stands to increase the production of merchantable wood despite constant site productivity, thereby increasing economic return for forest landowners.

The ultimate objective for production foresters is to maximize allocation of photosynthate to merchantable stemwood. Strides have been made in improving yield through various silvicultural practices. In many agricultural crops, enhanced yields have resulted primarily from a shift in carbon allocation to harvestable parts, rather than an actual gain in total productivity (Evans 1976).

The mechanisms for aboveground productivity and tissue carbon allocation are becoming more readily understood. Knowledge of belowground productivity patterns, however, lags far behind that of aboveground productivity. If enhancing productivity of merchantable aboveground tree components includes reallocation of available photosynthate from unharvestable belowground sinks, then the study of carbon allocation in the whole forest stand, both above- and belowground, is necessary. The objective of this preliminary study was to determine if there is evidence that different aboveground stand structures resulting from varying stand densities influence soil nutrient demand and subsequent belowground productivity.

CARBON ALLOCATION PATTERNS

Stand density is a factor that has significant influence on stand carbon allocation. Stand density is known to influence

tree crown morphology (Dean and Baldwin 1996a), which influences carbon allocation among stems, foliage, and branches (Ford 1982). These relations are complicated because both stand structure and productivity are associated with differences in age and site quality (Assmann 1970). However, Dean and Baldwin (1996b) have shown that stand density index (SDI), a measure of growing stock that includes quadratic mean diameter and trees per hectare (Reineke 1933), may be predicted solely from foliage density, mean live crown ratio, and canopy depth.

There is a positive relationship between stand density and stand foliage production. For a stand of a given stand density, the amount of foliage in a closed canopy stand is a function of the site quality. However, an increase in stand density has been shown to increase leaf area index (LAI) in loblolly stands (Dean and Baldwin 1996a). Stand density has also been shown to positively influence yearly needle fall, a measure of foliage production, in other pine stands (Gholz and others 1985, Gresham 1982).

There is also a positive relationship between stand density and stand stemwood production that is related to changes in canopy structure. Canopy structure is the result of many simultaneous processes including light penetration, height growth, crown lifting, and intercrown abrasion (Dean and Long 1992). After the onset of competition at crown closure, foliage is driven to the top of the canopy as a result of the natural pruning of lower branches (Mar: Mohler 1947). Wind action on the crown of a tree creates a bending stress on the stem, and as the crown midpoint becomes higher, coupled with an increase in the amount of foliage associated with increasing stand density (Dean and Baldwin 1996a), there is an increased load placed on the stem (Dean and Long 1986). Bending of the stem also

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increases the resistance to flow of water in the stem so that more sapwood is needed to transport the same amount of water to the foliage (Dean 1991). Therefore, as stand density and the subsequent physical load on the stem is increased, the carbon sink strength of the stem increases.

The amount of stand branchwood produced, however, is negatively related to stand density. Trees in sparser stands have deeper and wider canopies than do those in denser stands (Dean and Baldwin 1996a) and, therefore, must allocate a greater percentage of total net primary production (TNPP) toward the production and maintenance of branches to support the equilibrium level of foliage. In summary, then, as stand density increases, stand foliage and stemwood biomass production increase, while stand branchwood production decreases.

Another major sink for carbohydrates is production of the fine-root system. Indeed fine root production has been estimated to consume 30-70 percent of TNPP (Santantonio 1989) and has been shown to be inversely related to nutrient and water availability (Gower and others 1992).

On sites of equal nutrition, the belowground proportion of TNPP should correlate with the aboveground demand for nutrients and water according to the functional balance equation (Davidson 1969), which states that as aboveground nutrient demands increase, fine-root production will increase to meet that demand. Nutrient demands will vary during ontogeny (Imsande and Touraine 1994) with the greatest demands being placed on the nutrient reserves of a site during the early stages of stand development when the stand is approaching maximum leaf area (Switzer and others 1968). All else being equal, though, stands with a higher aboveground nutrient demand should allocate more carbon to belowground productivity to meet that demand and maintain a functional balance.

Switzer and others (1968) found that the nitrogen concentration of foliar, branch, and stemwood tissue to be 1.08 percent, 0.23 percent and 0.06 percent nitrogen, respectively, in 18-year-old loblolly pine trees, exhibiting little change with stand age. Foliar nitrogen concentration was 18 times greater than that of stemwood, representing the greatest portion of a stand's nutrient requirements, averaging 80 percent for all nutrients (Switzer and Nelson 1972). Because stand density influences the proportion of different aboveground tree tissues in a stand and those tissues vary in nitrogen concentration, stand density should also affect nutrient uptake and subsequent belowground biomass production if a functional balance exists. This preliminary study investigated the above hypothesis to determine if evidence existed to warrant a conclusive study.

METHODS

The study site was located on the Lee Memorial Forest in southeast Louisiana. The site annually receives 1620 mm precipitation, and has a mean low and high temperature of 12.5 °C and 25.5 °C, respectively. Soil there is a Ruston series fine-loamy, siliceous, thermic typic paleudult.

Four 25x25-m plots were established after a 1981 clearcut and planted with loblolly pine (*Pinus taeda* L.) seedlings, two on a 1.22x1.22-m spacing, and two on a 2.44x2.44-m spacing. Prior to data collection, understory vegetation on the plots was felled and drug off-site. Then plots were treated with the herbicide imazapyr to reduce variability from interspecific competition. To minimize edge effects, measurements were restricted to an inner 20x20-m plot.

Each tree in each plot was numbered and measured for outside bark d.b.h., total height, and height to the base of the live crown before the 1993, 1994, 1995, and 1996 growing seasons. Allometric equations were derived from an onsite destructive harvest in November 1994, when leaf area consisted primarily of foliage produced in the previous growing season, and served to give estimates of biomass for each of the aboveground tissue types and leaf area. Annual stand-level, aboveground production for each tissue type in each plot was calculated as the difference in biomass (as determined from the allometric equations) between two measurement periods. Trees that died between measurement periods were assumed to contribute no growth to stand-level production.

Nitrogen concentrations of each of the aboveground tissue types were taken from values cited by Switzer and others (1968), in which the foliar, branch, and stem nitrogen concentrations were 1.08 percent, 0.23 percent, and 0.06 percent nitrogen, respectively. Foliar retranslocated nitrogen that was assumed to be available for a single growing season was estimated to be 58 percent of the total nitrogen located in foliage that senesced the previous fall (Birk and Vitousek 1986). Stand-level nitrogen demand of the soil for a growing season in each plot was then calculated as the sum of the production of each tissue type for that growing season, multiplied by the nitrogen concentration of each tissue type, and then subtracting the estimate of nitrogen retranslocation.

Belowground root production was estimated by two minirhizotron censuses taken in the summer of 1996. For each of 10, clear PVC tubes placed randomly within each plot, fine roots that intersected one of three transects were counted and summed to give a total number of fine-root intersections per tube.

Since differences in stand age and fertility affect relations between production and leaf area (Gholz and others 1986, Waring and Schlesinger 1985), analysis was limited to plots of identical age and similar site quality (Smith and Long 1989). However, data were blocked into two sites as a result of a fertility gradient across the study area. Both sites 1 and 2 included a 1.22x1.22-m spacing plot and a 2.44x2.44-m spacing plot, but unpublished data show site 1 to have a greater nitrogen availability.

RESULTS AND DISCUSSION

Results, using a 3 year mean of the 1993, 1994, and 1995 growing seasons, showed that as SDI increased, total aboveground production increased (fig. 1). As predicted, on both sites, as SDI increased, foliage and stemwood

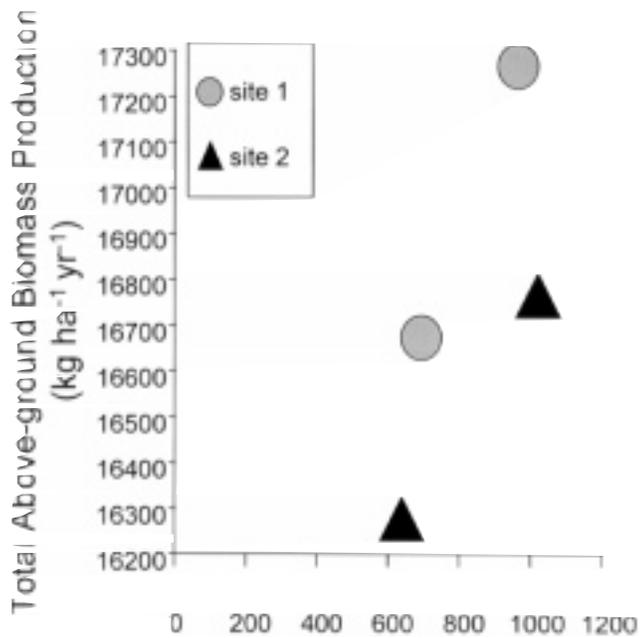


Figure 1—Total stand level aboveground biomass production as a function of stand density index.

production increased while branchwood production decreased. It was also found that the more fertile site 1 plots produced more aboveground biomass in all tissue types than the less-fertile site 2 plots.

As SDI increased, soil nitrogen demands also increased (fig. 2), primarily as a result of increased production of nitrogen-rich foliage on the denser plots. Indeed, over 85 percent of the total annual nitrogen demand in each plot was attributed to foliage. Again, the more fertile site 1 plots had a greater aboveground nitrogen demand.

Belowground fine-root intersections increased as SDI and aboveground nitrogen demands increased (fig. 3), giving support for a functional balance. Also, a greater number of root intersections per unit of nitrogen demand were recorded on the less-fertile site 2, suggesting that on these plots, a greater percentage of TNPP was allocated to fine-root production to meet aboveground demands.

Although total annual stemwood production and stemwood production per unit of leaf area increased with increasing SDI, as has been shown in previous studies (Long and Smith 1990, Smith and Long 1989), stemwood production per unit leaf biomass decreased with increasing SDI (fig. 4). This is assumed to be the result of a greater percentage of TNPP being partitioned to fine-root production in the denser stands. Santantonio (1989) has shown that a strong, negative relationship exists between fine-root and stemwood production in closed canopy stands. Although there is a greater amount of foliage biomass produced in the denser plots, it appears that foliage there is less efficient at producing photosynthate, perhaps as a result of an increase in self-shading caused by increased foliar density, a characteristic of denser stands (Dean and Baldwin 1996a).

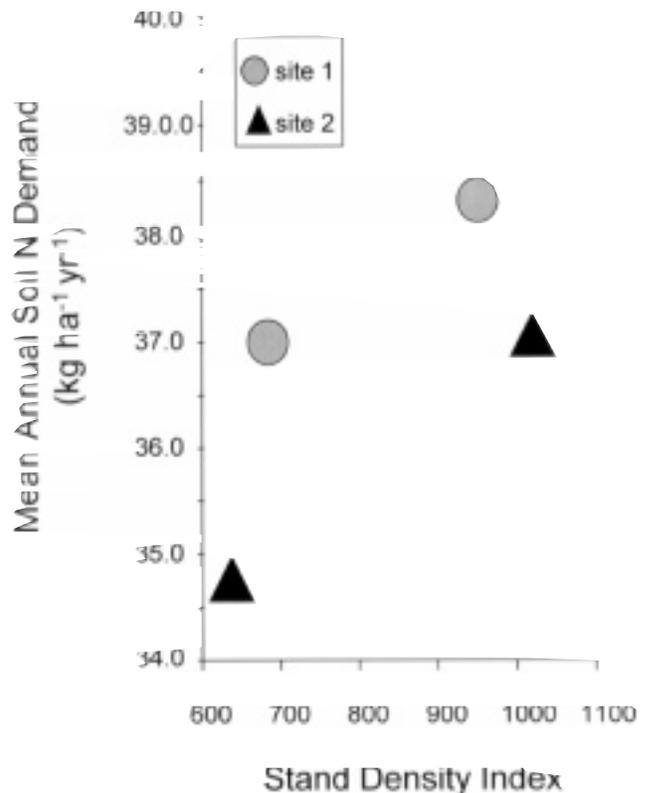


Figure 2—Stand level aboveground nitrogen demands as a function of stand density index.

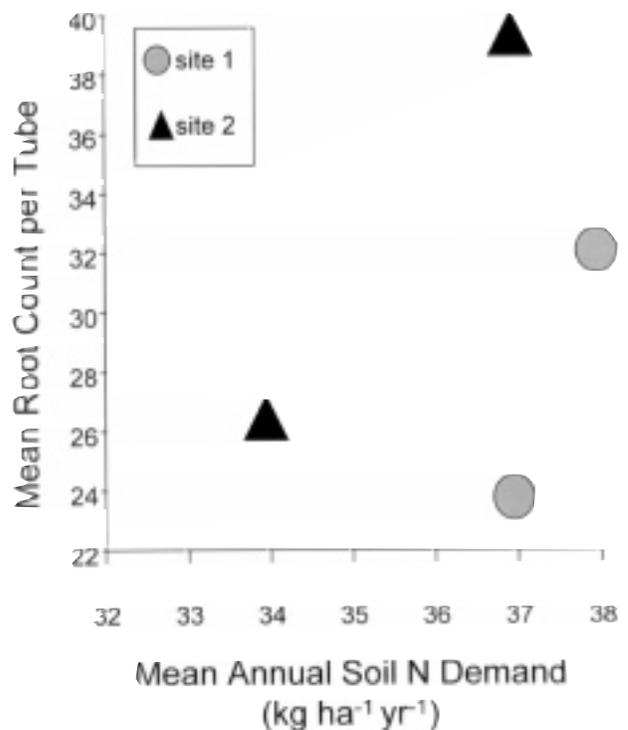


Figure 3—Mean number of root intersections counted as a function of aboveground nitrogen demand.

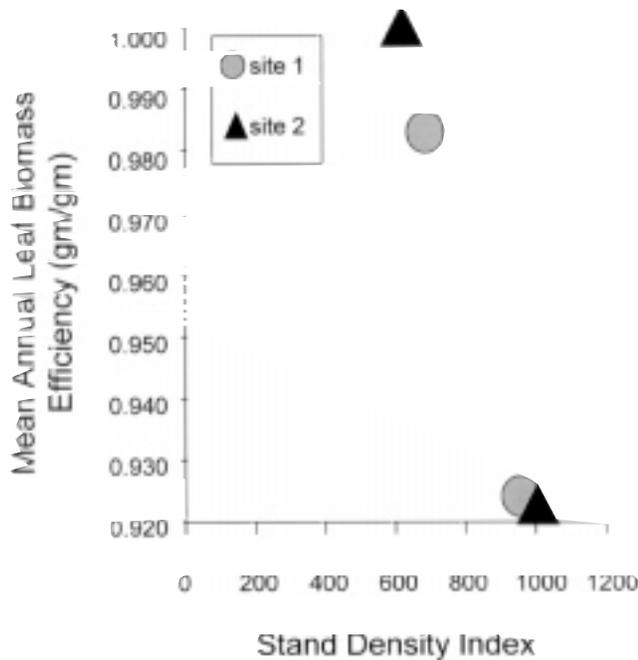


Figure 4—Mean stemwood produced per unit of leaf biomass as a function of stand density index.

One means of reallocating carbon from unharvestable belowground sinks to harvestable aboveground stemwood, then, may be by increasing foliar efficiency through various silvicultural means. For example, foliage does not contribute to stemwood production until maintenance respiration requirements of supporting branches are met (Ford 1975). Foliage in the shaded lower crown, then, would contribute little to production as a result of lowered photosynthetic rates and increased branch maintenance, yet would retain a carbon cost associated with production of fine-root biomass to meet foliar nutrient requirements. By pruning lower branches, a forester may lose little in production, but gain significant amounts of carbon that would have been allocated to fine-root production that supported the low efficiency foliage, thereby gaining in net carbon that could be used for stemwood production.

CONCLUSIONS

Results showed that as stand density increases, changes in aboveground carbon allocation increases both nitrogen demand and belowground productivity to meet that demand. Also, more belowground production is needed on less fertile sites to meet similar demands, decreasing photosynthate that could potentially be used in aboveground production. Therefore, more photosynthate may be available to aboveground sinks as sites become more fertile (through fertilization) or as foliage become more efficient.

The lack of plots in this preliminary study limited statistical analysis, but did provide insightful data. Therefore, a more conclusive study is in progress that will have greater statistical power and include analysis with additional stand densities and species.

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IMPACT OF NANTUCKET PINE TIP MOTH ATTACK ON LOBLOLLY PINE— A SOUTH-WIDE SUMMARY

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Abstract—The Nantucket pine tip moth (*Rhyacionia frustrana* Comst.) is the most important insect pest of young loblolly pine (*Pinus taeda* L.) in the Southern United States. Trees less than 10 ft. tall can be heavily infested by this insect. The greatest growth impact occurs during the first two to three growing seasons after planting. This paper presents a summary of 24 tip moth impact studies from 9 States (Arkansas, Florida, Georgia, Louisiana, Maryland, Mississippi, South Carolina, Tennessee, and Texas). Sixteen of the 24 were measured in more than 1 year. The plantation ages at the time of measurement ranged from 2 to 16 years. Comparisons were made between the untreated check plots and insecticide-treated plots in each study. Differences in height between treated and check plots averaged 2.4 ft./tree and ranged from 0 to 9.5 ft./tree. Differences in diameter averaged 0.5 in./tree and ranged from 0 to 2 in./tree. Average cubic foot volume per tree impact was 0.5 ft³/tree while there was an average difference in volume/acre of 4.0 cords. Few of these studies have any meaningful documentation of tip moth infestation levels; therefore, it is not possible to relate growth impact to tip moth attack. Consequently, estimates of impact represent averages for variable and unknown levels of tip moth damage, overestimating impact where infestation levels are low and underestimating impact where attack levels are high. In addition to growth impact, tip moth attack results in some product degrade due to an increase in the number of knots per linear foot of lumber, and an increase in the volume of compression wood leading to reduced pulp yields. Intensive loblolly pine plantation management is apparently related to the severity of tip moth impact; therefore, the Nantucket pine tip moth will remain a serious insect pest that forest managers will have to deal with in the future.

INTRODUCTION

The Nantucket pine tip moth (NPTM) (*Rhyacionia frustrana* Comst.) is one of the most important insect pests of young loblolly pine (*Pinus taeda* L.) in the Southern United States. Trees less than 10 ft tall can be heavily infested by this insect. The greatest growth impact occurs during the first two to three growing seasons after planting. Historically, the NPTM has been considered a minor pest of loblolly pine. However, it is now perceived as an important pest in young pine plantations. This change has coincided with the increase in the number of loblolly pine plantations and the intensity of management in these newly planted stands.

Information on the cost and benefits of managing of this insect is necessary before a control program for the NPTM can be implemented. Of special importance is information on NPTM impact on loblolly pine growth and yield. Several growth impact studies have been published; however, there has been no systematic attempt to analyze this data. This paper is an attempt to assemble and summarize the existing data on the impact of the NPTM on loblolly growth and yield.

METHODS

The literature on NPTM was searched to identify studies on the impact of attack on its pines. To be included in this analysis the studies had to meet certain criteria. These criteria were that data from untreated check and insecticide-treated plots be available for a single location, that the pine species included loblolly pine, and that the trees were planted. Information on height, diameter, and volume were summarized for each site. These data were subjected to statistical analyses which included calculation

of means and standard deviations of the variables of interest. The data was also analyzed by age class since the studies included trees of various ages. Measurement data from different years at the same site were available for a few studies. The data were grouped and analyzed by measurement period. Specific detail on the data for each individual study can be found in the appendix.

RESULTS AND DISCUSSION

Data were obtained from 24 separate studies that met the criteria for inclusion in this paper. These studies resulted in 42 observations on height growth (table 1), 37 observations on d.b.h. (table 1), 16 for cordwood volume/acre (table 3), and 13 for cubic foot volume/tree (table 2). The average difference in total tree height is 2.4 ft/tree (sd=1.93, n=42), in d.b.h. it is 0.5 in./tree (sd=0.38, n=37), in volume/acre it is 4.0 cords (sd=4.8, n=16), and in volume/tree the difference is 0.5 cu. ft. (sd=0.50, n=13). These studies represent a variety of sites varying in cultural treatment, site productivity, intensity and frequency of tip moth control, and unknown but varying levels of tip moth infestation levels. Consequently, these average differences will probably overestimate tip moth impact where infestation levels are low, and underestimate impact where infestation levels are high.

Changes in Height and Diameter Over Time

Since these means are over all sites and ages, it is of interest to stratify the data by age classes. Table 4 shows the statistics for height and diameter grouped into four classes with median ages of 3, 5, 8, and 15 years. However, any trends in this table are difficult to interpret since many of the sites in each age class came from separate studies. Therefore, the data were further restricted

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Table 1—South-wide summary of growth response of loblolly pine to tip moth control

Location	Age	Height			Diameter at breast height.			Note ^a
		Trt.	Chk.	Dif.	Trt.	Chk.	Dif.	
		----- Ft -----			----- In -----			
Calhoun, TN	5	7.0	6.6	0.4	-	-	-	(1)
Warren, AR	8	18.2	16.3	1.9	3.6	3.1	0.5	(2)
Beltsville, MD	4	9.8	4.9	4.9	-	-	-	(3)
Beltsville, MD	10	24.5	16.5	7.9	5.5	3.5	2.0	(3)
Clemson, SC	2	3.6	3.3	0.3	-	-	-	(4)
Louisville, GA	3	8.4	6.6	1.8	0.9	0.5	0.4	(5)
Louisville, GA	5	17.8	14.6	3.2	3.1	2.4	0.7	(5)
Rincon, GA	3	11.3	9.9	1.4	1.8	1.5	0.3	(5)
Rincon, GA	5	21.4	20.0	1.4	3.8	3.6	0.2	(5)
Owensville, AR	6	12.0	10.0	2.0	1.8	1.5	0.3	(6)
Owensville, AR	8	16.0	13.5	2.5	3.0	2.5	0.5	(6)
Owensville, AR	12	27.5	25.0	2.5	5.1	4.6	0.5	(6)
Umpire, AR	6	11.0	9.0	2.0	1.6	1.2	0.4	(6)
Umpire, AR	8	16.0	13.0	3.0	2.9	2.4	0.5	(6)
Umpire, AR	12	28.5	27.0	1.5	5.2	4.8	0.4	(6)
Homer, LA	5	18.6	16.3	2.3	-	-	-	(7)
Homer, LA	14	44.4	43.9	0.5	-	-	-	(7)
Crossett, AR	6	12.0	9.9	2.1	2.1	1.5	0.6	(8)
Crossett, AR	16	39.0	39.0	0.0	6.6	6.4	0.2	(8)
Oxford, MS	6	20.0	17.3	2.7	3.5	3.2	0.3	(8)
Oxford, MS	16	52.0	47.0	5.0	7.5	7.2	0.3	(8)
Alexandria, LA	5	8.6	7.9	0.7	1.4	1.3	0.1	(8)
Alexandria, LA	15	47.0	44.0	3.0	6.5	6.4	0.1	(8)
Brewton, AL	5	14.8	14.3	0.5	1.9	1.6	0.3	(8)
Brewton, AL	15	46.0	46.0	0.0	7.2	6.9	0.3	(8)
Harrison, AR	5	10.9	10.2	0.7	1.8	1.6	0.2	(8)
Harrison, AR	15	36.0	35.0	1.0	6.9	6.6	0.3	(8)
Marianna, FL	5	11.4	7.5	3.9	1.7	1.4	0.3	(8)
Marianna, FL	15	27.5	18.0	9.5	5.4	3.6	1.8	(8)
Nacogdoches, TX	5	18.0	15.4	2.5	3.1	2.7	0.4	(8)
Nacogdoches, TX	15	51.0	48.0	3.0	7.1	6.8	0.3	(8)
Sewanee, TN	5	11.2	11.3	-0.1	1.8	1.8	0.0	(8)
Sewanee, TN	15	45.0	45.0	0.0	7.8	7.5	0.3	(8)
Hope, AR	6	16.5	11.4	5.1	3.5	2.3	1.2	(9)
Hope, AR	13	35.0	30.5	4.5	6.6	6.1	0.5	(9)
Hope, AR	8	24.2	20.2	4.2	5.6	4.7	0.9	(10)
Hope, AR	16	44.4	42.9	1.5	9.7	8.9	0.9	(10)
El Dorado, AR	7	20.4	17.4	3.0	4.0	3.7	0.3	(11)
Hot Springs, AR	4	11.0	7.4	3.6	1.8	0.9	0.9	(12)
Paron, AR	5	8.7	7.4	1.3	1.3	1.0	0.3	(12)
Alikchi, OK	5	12.4	11.6	0.8	2.4	2.1	0.3	(12)
Winthrop, AR	3	11.8	9.9	2.8	2.0	1.3	0.7	(12)

^a Notes are located in the appendix.

to measurements at two time periods for the same site. The early measurement (T1) occurred when trees had been in the field for 5 to 8 years. The ages at the second measurement (T2) occurred at 12 to 16 years. The difference in tree height at T1 was 2.20 ft/tree (sd=1.53,

n=13), while at T2 it was 2.58 ft/tree (sd=2.68, n=13). Difference in d.b.h. at T1 was 0.42 in./tree (sd=0.32, n=12), while at T2 it was 0.49 in./tree (sd=0.46, n=12). This analysis shows that height and diameter differences are maintained through time.

Table 2—South-wide summary of tip moth control cubic foot volume per tree

Location	Note ^a	Age	Trt.	Chk.	Diff.	Pct. diff.
-----Cubic feet-----						
Louisville, GA	(5)	5	0.42	0.21	0.21	100
Rincon, GA	(5)	5	0.91	0.73	0.18	25
Beltsville, MD	(3)	9	2.29	0.60	1.69	282
Umpire, AR	(6)	12	1.58	1.31	0.27	21
Owensville, AR	(6)	12	1.47	1.14	0.33	29
Alexandria, LA	(8)	16	3.77	3.30	0.46	14
Alexandria, LA	(8a)	16	3.58	3.30	0.28	8
Brewton, AL	(8)	16	3.24	3.02	0.22	7
Crossett, AR	(8)	16	2.77	2.61	0.16	6
Gulfport, MS	(8)	16	4.74	4.45	0.29	6
Harrison, AR	(8)	16	2.97	2.33	0.64	27
Many, LA	(8)	16	4.86	5.28	(-0.42)	(-9)
Marianna, FL	(8b)	16	1.43	0.25	1.18	472
Marianna, FL	(8c)	16	0.59	0.09	0.50	555
Nacogdoches, TX	(8)	16	5.38	4.27	1.11	26
Oxford, MS	(8)	16	6.26	4.78	1.48	31

^a Notes are located in the appendix.

Table 3—South-wide summary of tip moth control cordwood volume per acre

Location	Note ^a	Age	Trt.	Chk.	Diff.	Pct. diff.
----- Cords -----						
Louisville, GA	(5)	5	3.4	1.7	1.7	100
Rincon, GA	(5)	5	7.3	5.8	1.5	26
Owensville, AR	(6)	12	11.2	9.2	2.0	22
Umpire, AR	(6)	12	11.1	8.3	2.8	34
Hope, AR	(9)	13	26.1	22.0	4.1	19
Hope, AR	(10)	13	44.5	33.0	11.5	35
Alexandria, LA	(8)	16	32.5	29.7	2.8	9
Alexandria, LA	(8a)	16	31.7	29.7	2.0	7
Brewton, AL	(8)	16	21.5	26.2	(-4.7)	(-18)
Crossett, AR	(8)	16	23.2	22.5	0.7	3
Gulfport, MS	(8)	16	31.5	32.9	(-1.4)	(-4)
Harrison, AR	(8)	16	23.2	17.9	5.3	30
Many, LA	(8)	16	38.6	37.0	1.6	4
Marianna, FL	(8b)	16	11.1	2.0	9.1	455
Marianna, FL	(8c)	16	5.0	0.7	4.3	614
Nacogdoches, TX	(8)	16	36.7	24.7	12.0	46
Oxford, MS	(8)	16	49.7	37.9	11.8	31
Sewanee, TN	(8)	16	36.1	34.8	1.3	4

^a Notes are located in the appendix.

Table 4—Average loblolly pine height and diameter at breast height (d.b.h.) differences for insecticide-treated and untreated check plots by age class

Median age	Height diff.				D.b.h. diff.		
	Range	Mean	SD	N	Mean	SD	N
----- Years ----- ----- Feet----- ----- In -----							
3	3-4	2.40	1.83	5	0.53	0.18	3
5	5-6	1.90	1.34	18	0.39	0.28	16
8	7-10	3.75	2.17	6	0.78	0.62	6
15	12-16	2.46	2.68	13	0.49	0.46	12

Prediction of Differences in Height and Diameter

The data for differences of height and diameter for the early time period can be used to predict the difference in height and diameter at the later time period. This could be useful for calibrating growth and yield models to estimate long-term impact of NPTM attack on loblolly pine yield. Two equations were estimated using linear regression. The dependent variables were height/tree (H2) and d.b.h./tree (D2) at ages 12 to 16 years. The independent variables were height/tree (H1) and d.b.h./tree (D1) at ages 5 to 8 years. These equations were each based upon 12 observations. The equation for the height difference/tree is: $H2 = 0.888 + 2.767(H1) - 10.087(D1)$ (R-square=0.86). The equation for the difference in d.b.h./tree is: $D2 = 0.182 + 0.385(H1) - 1.280(D1)$ (R-square=0.60). This is just one example of the types of analyses which can be performed using the data from table 1.

Long-Term Volume Impact of Tip Moth Attack

The oldest NPTM studies that contain volume data are for 16-year-old stands of loblolly pine (table 3). The average volume difference at these sites ranged from -4.7 to 12 cords per acre. Only 2 of the 12 sites had negative volume differences. There is no evidence to suggest that the insecticide treatments were the cause of more volume in untreated check plots; therefore, it can be assumed that a negative value indicates there was no volume difference between treatments. Using this assumption, and substituting values of zero for the negative differences at these two sites, the average volume difference is 4.2 cords/acre (sd=4.4, n=12). This value is probably representative of the impact in loblolly pine stands subjected to low-intensity plantation management. These data also illustrate the high degree of between-site variability in impact which is typical of pine stands where the NPTM has been controlled.

Cade and Hedden (1987) used data from tip moth impact studies in two loblolly pine plantations in Arkansas to project volume impact at rotation. They projected the volume loss at a rotation age of 30 years in an unthinned

stand to be 2 to 6 cords/acre. Volume loss in a stand thinned once at age 20 and harvested at age 35 was projected to be 1 to 3 cords/acre and 300 to 700 b.f./acre. Hedden and others (1991) also used a growth-and-yield model to project volume loss from NPTM attack. The estimated volume loss in an unthinned stand at age 30 years was 6.2 cords/acre. They also projected that the volume loss in a stand thinned at age 20 with a final harvest at age 30 to be 0.6 cords/acre and 900 b.f./acre. This represents a loss of about 10 percent of the potential sawtimber yield for the stand. However, it should be noted that the actual yields at rotation may be greater or less than those projected in these studies, depending on many factors including level of tip moth control, site productivity, the type and intensity of plantation management, and local tip moth population levels.

Impact of Tip Moth on Product Quality

Volume loss due to tip moth attack is only one aspect of impact (Berisford and others 1989). The NPTM also causes significant product degrade. The larval stage of the moth mines both the terminal and lateral shoots of the tree. When the terminal bud is killed, the tree responds in one of two ways. A lateral branch will replace the dead terminal, or a fascicular bud will be released on the terminal. In the case where a lateral branch replaces the terminal, severe stem deformity and extensive formation of compression wood will occur. Where a fascicular bud is released, little deformity but significant compression wood formation will occur. Moreover, since attack on the terminal leader retards height growth, the branch whorls will be closer together which results in an increase in the number of knots per unit of height and, again, in an increase in the amount of compression wood due to knots.

The only study (Hedden and Clason 1979) that has attempted to quantify the impact of NPTM attack on product quality showed that 21-year-old loblolly pines attacked by pine tip moths, when compared to insecticide-treated trees, had twice as much compression wood in the lower 16 ft log. Based upon this study, pulp yields in the bottom of the 16 ft log of untreated trees would be reduced by 1.5 to 2.5 percent. Longitudinal shrinkage due to compression wood could result in studs with 3 to 5 times more crook than studs without significant compression wood (Gaby 1972). Studs from trees attacked by the NPTM had 11 percent fewer boards graded as 2D or better than studs from insecticide treated trees. Furthermore, degrade

due to knots was much higher in logs from attacked trees. After trimming, studs from untreated trees were degraded due to knots 51 percent of the time, but degraded only 20 percent of the time in studs from treated trees. Consequently, tip moth control should result in an increase in both product quantity and quality.

CONCLUSIONS

Nantucket pine tip moth attacks in young loblolly pine plantations result in a significant loss in the yield at harvest. Reductions of pulpwood volumes due to attack are projected to average 2 to 6 cords/acre. Losses in stands managed for sawtimber are estimated to range from 1 to 3 cords/acre and 300 to 1000 b.f./acre. Moreover, tip moth attack reduces sawtimber quality and pulp yields due to an increase in compression wood level and the number of knots in the lower stem. Actual impact from NPTM will ultimately depend upon the intensity of young plantation management, site productivity, the product being managed for, and many other interacting factors. However, control of the NPTM in young loblolly pine plantations should result in both enhanced quality and quantity of pine yield.

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APPENDIX

(Notes for table 1)

- (1) Mason, R.R. 1958. Study of tip moth effects on height growth in loblolly pine plantations: two year results. Hiwassee Forest Res. Note 3. Hiwassee Land Company. Calhoun, TN. 2 p. (5-year-old trees were sprayed three times during the summer of 1956.)
- (2) Grano, C.X.; Grigsby, H.C. 1968. Spraying southern pines not practical for tip-moth control. Res. Note SO-77. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 2 p. (Sprayed for 8 years using DDT.)
- (3) Lashomb, J.H.; Steinhauer, A.L.; Douglas, L. 1978. Impact studies of Nantucket pine tip moth populations on loblolly pine. *Environ. Entomol.* 7: 910-912. (Trees caged for 1 year and sprayed for 1 year. Data on early height growth is presented.)

Hedden, R.L.; and others. 1980. Impact of Nantucket pine tip moth attack on young loblolly pines. In: Barrett, J.P., ed. Proceedings of the first biennial southern silvicultural research conference. Gen. Tech. Rep. SO-34. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station: 238-241. (Presents eighth-year results of the above study, including data on volume and biomass impact).
- (4) Hedden, R.L.; Haugen, D.A. 1986. Impact of pine tip moth attack on loblolly pine seedlings. In: Phillips, D.R., ed. Proceedings of the fourth biennial silvicultural research conference. Gen. Tech. Rep. SE-42. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 535-537. (Tip moth controlled during the second year in the field.)
- (5) Berisford, C.W.; Godbee, J.F.; Ross, D.W. 1989. Impact of pine tip moth control, weed control, and fertilizer on growth and form of loblolly pine. In: Alfaro, R.I.; Glover, S.G., eds. *Insects affecting reforestation: biology and damage*. Forestry Canada, Pacific Forestry Centre, Victoria, BC, Canada: 130-136. [Tip moth controlled first 3 years in the field. Check means were the average of the no treatment and the fertilizer + herbicide (F + H) treatment. Treatment means were the average for the tip moth control (TMC) and the TMC + F + H treatments. Results for Rincon and Louisville in the fifth year are courtesy of C. W. Berisford.]
- (6) Cade, S.C.; Hedden, R.L. 1987. Growth impact of pine tip moth on loblolly pine in the Ouachita Mountains of Arkansas. *Southern Journal of Applied Forestry.* 11: 128-133. (Tip moth controlled second, third, and fourth growing seasons in the field. Treated means are the averages for the granule and spray-granule treatments.)
- (7) Shepard, R.K. 1973. The effect of tip moth control on height growth of loblolly pine. In: Shepard, R.K., ed. *Forestry Res. Reports*. ed. North Louisiana Hill Farm Experiment Station, Homer, LA: 55-58. (Tip moths were controlled for seven growing seasons after planting.)
- (8) Beal, R.H. 1967. Heavy tip moth attacks reduce early growth of loblolly pine. Res. Note SO-54. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 3 p. (Effective control during second and third growing seasons in the field. Phorate, 10 grams of 10 percent granular, was applied in fourth, fifth, and sixth seasons, but this rate was not high enough for effective control at these ages.)

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THE NOT-SO-SUDDEN RESULTS OF THE SUDDEN SAW LOG STUDY— GROWTH AND YIELD THROUGH AGE 45

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Abstract—The Sudden-Saw Log Study, located near Crossett, AR, was established to test the hypothesis that loblolly pine plantations can produce sawtimber on good sites in 30 years. Study measurements reported at stand age 33 years showed that the hypothesis is true. Fortunately, the study was not terminated at that time. Inventory data were also collected at stand ages 36, 39, and 45 years. By stand age 45, average Doyle board-foot volume sawtimber yields for all treatments were not significantly different, averaging 21,889 bf/acre, although the mean diameter of trees that received intensive management (20.4 inches) was 38 percent greater than that of trees receiving the control treatment (14.9 inches). The control treatment always produced the greatest cubic-foot volume (9,422 ft³ at age 45), and after age 33 led all other treatments in predicted financial returns.

INTRODUCTION

In February 1954, a 9-year-old loblolly pine (*Pinus taeda* L.) plantation located on an abandoned cotton field near Crossett, AR, was selected for use in a growth-and-yield study (Burton 1982, Burton and Shoulders 1974). The stand had been planted at a spacing of 6 ft by 6 ft (1,210 trees/acre) in 1945. By 1954, survival averaged 1,100 trees/acre, and the 50-year site index was projected to be between 90 and 100 feet. The study objective was "...to determine whether a plantation on a good site (site index = 90) could be managed to produce good quality sawtimber on a short rotation by combining early thinning, understory vegetation control, and pruning" (Baker and Bishop 1986).

The study was officially closed at age 33. Results were reported in Burton and Shoulders (1974), Burton (1982), Taylor and Burton (1982), and Baker and Bishop (1986). However, the stands were never cut and the trees were remeasured at ages 36, 39, and 45. Management, except for occasional mowing of the plots to facilitate tours, had discontinued at age 30. This paper reports the effects of stand treatments on growth and yield since study inception, with emphasis on results at the later ages.

METHODS

Four thinning treatments were replicated three times in randomized blocks. Two treatments began immediately (at age 9) and two began at age 12, when the average tree had attained merchantable pulpwood size. The four treatments were:

Sawtimber only—All noncrop trees and all but 100 crop trees/acre were cut at age 9. Stands were thinned every 3 years thereafter to 76 trees/acre by age 19 and to 41 trees/acre at age 30.

Sawtimber pulpwood—Thinnings at age 9 and 12 removed noncrop trees whose crowns were within 5 feet of crowns of the 100 crop trees. The last noncrop trees were removed at age 15. Further thinnings at 3-year intervals left 80 trees/acre at age 19 and 52 trees/acre at age 30.

Delayed sawtimber—Stands were reduced to 100 crop trees/acre at age 12 and thinned every 3 years thereafter until 45 trees/acre remained at age 30.

Control—Plots were thinned, mainly from below, to a basal area of 85 ft²/acre at age 12 and every 3 years afterward through age 30. The thinnings reduced stand density from 712 stems/acre at 12 years to 116 stems/acre at 30 years.

The timing and severity of later thinnings were based on periodic d.b.h. growth. Crop trees in the intensive-treatment plots were pruned from the ground to about one-half their total height after the first thinning and every 3 years afterward until clear length averaged 33 feet at age 24. Also, beginning at age 19, the woody understory was mowed every 2 years in the intensively managed plots.

MEASUREMENTS AND ANALYSIS

The d.b.h. of all trees was obtained at every measurement date. Total height and height to the base of the live crown, for all crop trees, were measured from age 12. Volumes reported in earlier papers were read from a standard volume table (USDA Forest Service 1976) for stands aged 12 to 18 and were calculated by the STX Program (Grosenbaugh 1967) for stands aged 21 to 33. All total inside-bark cubic-foot volumes and Doyle inside-bark board-foot volumes (merchantable height to an 8-inch inside-bark top diameter) reported here were calculated by means of volume and taper equations (Baldwin and Feduccia 1991). The Doyle board-foot volume measure was selected because its use is mandated by law in timber sales in most of the Southern United States (Baker and Bishop 1986). Volume yields included the accumulated cut yields for each of the treatments.

Yield curves were developed by fitting nonlinear regressions to the volume yield data. The model was $yield = a[1 - \exp(-b \cdot age)]^c$, where a, b, and c are the parameters estimated. Mean and periodic annual volume increments, MAI and PAI, respectively, were then calculated from these smoothed curve values. The mean diameters reported are

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prethinning values for each measurement period; the use of prethinning values minimizes the effect that thinning from below has on diameter. Differences among treatment means were tested by analysis of variance and Duncan's multiple-range test at the $\alpha=0.05$ level (SAS Institute 1989).

Pretax soil expectation values (SEV's) for harvest ages 30, 33, 35, 39, and 45 were calculated for each treatment so that the economics of the treatments could be compared. Current costs of management activities were gathered from forest managers, scientists, and vendors of forestry services. Louisiana stumpage prices for sawtimber and pulpwood were taken from estimates made by Timber Mart South, Inc. For each harvest, stumpage prices over a 2-year period were averaged to minimize the impact of stumpage price fluctuations on the analysis. The stands were not fully merchandized for quality products that might be obtained from stands of heavily pruned larger diameter timber. A more definitive analysis might include analysis of timber quality and a more thorough consideration of the impact of logging costs.

Some of the procedures or practices employed in the study and reflected in the economic analysis, such as the close 6-ft by 6-ft planting density, frequent mid-rotation mowing to control vegetation, and a two-log pruning regime, are not considered cost effective and thus are not utilized in the present economic climate. The fixed costs of holding the land in forestry—property taxes and miscellaneous management costs—were also not considered in this analysis. The total investment costs of the sawtimber-only, sawtimber-pulpwood, and delayed-sawtimber treatments exceeded \$660/acre, whereas the total investment cost for the control treatment was only \$161/acre. A real discount rate of 4 percent was used to calculate SEV's. The assumption was made that all prices and costs increased at the rate of inflation.

RESULTS

Only the control treatment was thinned to a target basal area before age 27, so the residual basal areas for the other treatments varied, mainly according to the number of trees cut at each thinning. Basal area was always highest for the control treatment. At age 45, basal area for the control treatment was about 40 ft²/acre more than basal areas for the sawtimber-only and delayed-sawtimber treatments (98 ft² and 102 ft², respectively), and about 30 ft²/acre more than the basal area for the sawtimber-pulpwood treatment (109 ft²).

Quadratic mean diameter (d.b.h.) was highest for the sawtimber-only treatment throughout the study. The age-45 diameters for all of the intensive treatments did not differ significantly from treatment to treatment (fig. 1). The mean diameter for the control treatment (14.9 inches) was 27 percent less than the average for the other three treatments (20.4 inches). Thus, trees in the intensively managed stands reached sawtimber size before the others did and maintained at least a 27-percent size advantage from age 18 through age 45.

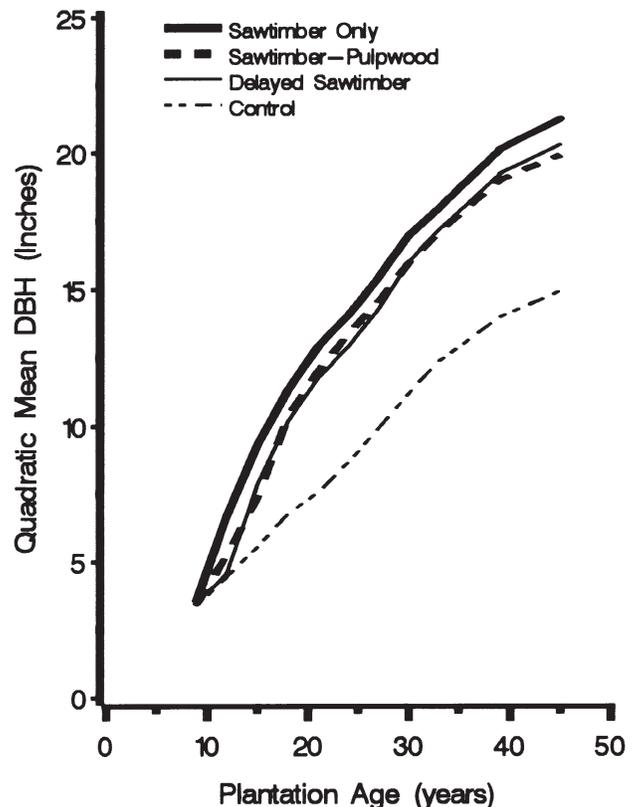


Figure 1—Trends in prethinning quadratic mean diameter. Lines join data points for the remeasurement years.

There was no significant difference in mean total crop-tree height between treatments at any remeasurement year. Height averaged 94 feet at age 45. Extrapolation of these results suggests that total height will be near 100 feet at age 50, indicating that site index for the study plots is at the upper end of the range predicted (90 to 100 feet) at study installation (Burton 1982).

As would be expected, the control treatment always carried the highest total cubic-foot volume because it had the most trees per acre throughout the study. At age 45, total volume yield for the control treatment was 9,422 ft³/acre, compared to an average yield of 6,642 ft³/acre for the intensively managed treatments. These treatment yields, and those reported below, include all volumes cut at earlier ages.

At age 30, when this study was designed to end, the intensive treatments had produced about twice the board-foot volume produced by the control treatment (table 1). Fifteen years later, however, board-foot volume for the control treatment, (19,778 bf/acre) had nearly caught up with the average volume yield of the other treatments (22,592 bf/acre) and was not significantly different from the other yields. Board-foot volume production of the control stand may even exceed that of the intensively managed stands in a few years (fig. 2). However, all treatments were near their predicted maximum level of annual board-foot volume productivity, so quantitative extrapolations are not warranted. Mean annual increment for cubic-foot volume maximized at age 32 for the delayed-sawtimber treatment, while the

Table 1—Saw log volume yield^a in Doyle board foot per acre for each measurement age and treatment

Plantation age	Treatment ^b			
	Sawtimber only	Sawtimber pulpwood	Delayed sawtimber	Control
<i>Years</i>				
9	0	0	0	0
12	0	0	0	0
15	176	0	13	0
18	2,008	1,007	869	24
21	3,998 a	2,836 b	2,937 b	116 c
24	6,329 a	5,228 b	5,378 b	995 c
27	8,955 a	7,897 b	8,078 ab	2,846 c
30	11,415 a	10,402 a	10,335 a	5,151 b
33	13,527 a	12,903 a	12,699 a	8,034 b
35	14,811 a	14,636 a	14,577 a	9,928 b
39	18,663 a	18,759 a	18,468 a	14,614 b
45	22,622 a	22,611 a	22,544 a	19,778 a

^a Yield is the total board-foot volume at the listed age plus the sum of all previously harvested volume

^b Treatment means for ages 21 and above were tested for statistically significant differences with $\alpha=0.05$ using Duncan's multiple-range test. Means in the same row succeeded by the same letter are not significantly different (SAS Institute 1989).

maximum was achieved at age 35 for all other treatments. The maximums for Doyle board-foot volume are projected to occur at about age 48 for the intensively managed treatments and at age 52 for the control treatment (fig. 3).

Despite the very high investment costs of the intensive-management treatments, the SEV's of these treatments were high and reached a maximum at plantation age 39 (table 2). The delayed-sawtimber stand had the highest SEV (\$1,892/acre) among the three high-investment treatments, followed by sawtimber-pulpwood (\$1,867/acre) and sawtimber-only (\$1,732/acre). The control treatment, which was inexpensive to establish, had the highest SEV (\$2,049/acre).

DISCUSSION AND CONCLUSIONS

The most significant change since the report by Burton (1982) at stand age 33 was the increase in board-foot volume and value of the timber in the control-treatment plots. That treatment passed the others financially after 33 years of growth. Of course this trend was not unexpected—only the time of occurrence was unknown. In their report of the age-30 results, which included an analysis showing that the intensive-management treatments were the best financial investment, Baker and Bishop (1986) stated: "...if the rotation were lengthened to 40 or 50 years, the results of the financial analyses would change markedly, with the

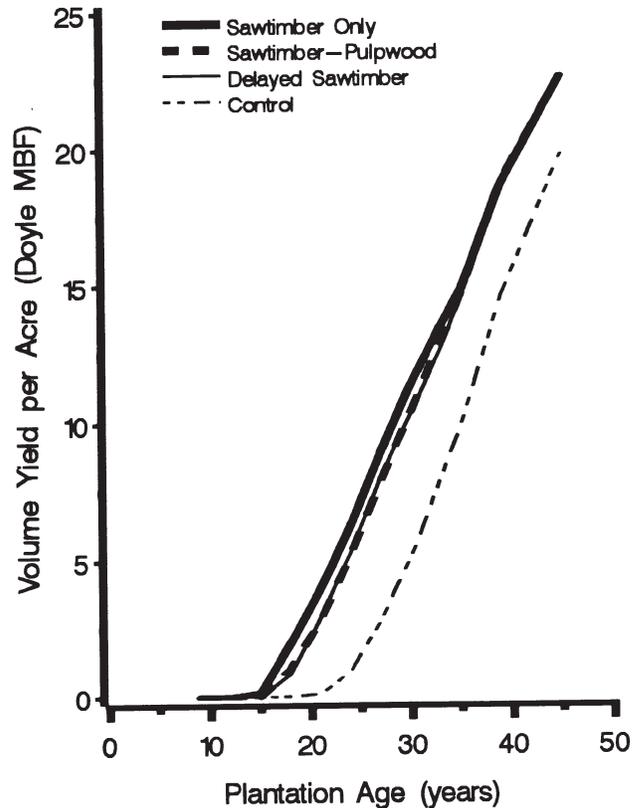


Figure 2—Trends in inside bark, Doyle board-foot volume yield per acre through age 45. Lines join data points for the remeasurement years.

Table 2—Soil expectation values (4-percent discount rate) for each treatment at each inventory starting from age 30

Treatment	Plantation age (years)				
	30	33	35	39	45
----- Dollars -----					
Sawtimber only	1,502	1,591	1,606	1,732	1,636
Sawtimber-pulpwood	1,535	1,674	1,737	1,867	1,727
Delayed sawtimber	1,548	1,683	1,775	1,892	1,791
Control	1,482	1,721	1,828	2,049	2,036

conventional management undoubtedly improving in investment ranking."

However, our financial analysis does not necessarily show that intensive management does not pay. Management costs could be lowered considerably. For example, the intensive-management plots could have been established with fewer trees/acre, pruning fewer times to a one-log height, and mowing less often or not at all. Also, it may be the case that the proportion of export-quality sawtimber is higher for the intensive treatments than for the control treatment, thus implying higher value of the intensive

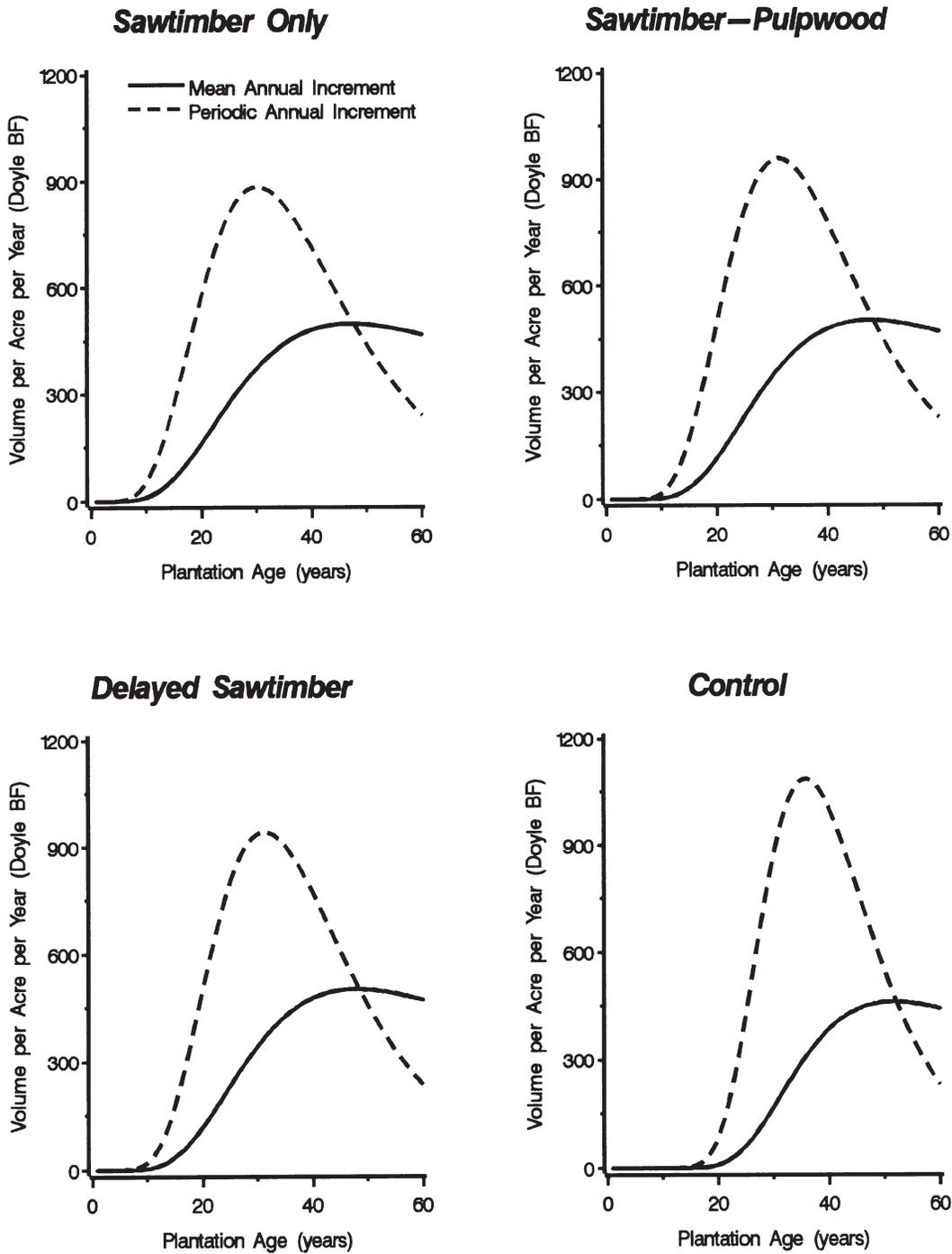


Figure 3—Regression curves for mean and periodic annual increment in Doyle board-foot volume per acre. Curves are extrapolated to stand age 60.

treatment products. Any of these adjustments could make the intensive management scenarios more profitable.

The objective of achieving sawtimber-sized loblolly pine on good sites in 30 years or less is indeed obtainable and can be obtained profitably. However, measurements made at older stand ages show that overall profits can be greater for conventionally managed stands than for intensively managed ones if stands are not harvested by age 33. It is recommended that, as Baker and Bishop (1986) proposed

earlier, landowners employing sudden-saw log silviculture use wider planting spacings, commercial thinnings only, pruning of only the very best trees to just one log-length, and early understory control to insure maximum production. Additionally, site preparation and fertilization should be considered for use on cutover lands.

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DIAMETER DISTRIBUTIONS AND BASAL AREA OF PINES AND HARDWOODS 12 YEARS FOLLOWING VARIOUS METHODS AND INTENSITIES OF SITE PREPARATION IN THE GEORGIA PIEDMONT

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Abstract—Twelve years after various methods and intensities of site preparation in the Georgia Piedmont, diameter distributions and basal area (BA) of pines and hardwoods varied considerably among treatments. Site preparation reduced hardwood basal area to 36 percent of that observed in clearcut-only plots. As a result, planted-pine BA in the presence of site preparation was 2.7 times that observed in its absence. Site preparation by manual cutting of residual trees resulted in a volunteer-pine BA of over three times that observed in mechanically prepared plots. We inferred that tillage treatments increased planted-pine BA through improvements in soil characteristics. In treatments in which the planted pines were under severe competition from hardwoods or volunteer pines, their diameter distributions were positively skewed (many small and few large individuals). In treatments of greater site-preparation intensity, diameter distributions approached a normal distribution.

INTRODUCTION

Silviculture often mimics natural disturbances to create desirable stand structures (Smith and others 1997). Specifically, silvicultural treatments select for the growth form, size, or species of trees that have the greatest competitive advantage during specific stages of stand development (Oliver and Larson 1996). An appropriate time for manipulating stand structure of pine plantations is after crown closure and during stand differentiation, when potential crop trees can be identified and recruited into the upper crown classes.

In this paper, we compare diameter distributions and basal area of pines and hardwoods among various methods and intensities of site preparation in the Georgia Piedmont. The results we describe supplement the findings of a previous paper on these data (Harrington and Edwards 1996).

METHODS

Study Site and Treatments

The study was conducted at an existing site-preparation experiment in the lower Piedmont of Georgia located on the Hitchiti Experimental Forest, 18 miles north of Macon. In spring 1980, the previous old-field stand of loblolly pine (*Pinus taeda* L.) was clearcut and nonmerchantable trees (primarily hardwoods) were left standing. Thirty 2-acre plots were located, and one of the following treatments was randomly assigned to each:

- (1) Clearcut only: absence of site preparation; residual (nonmerchantable) trees retained.
- (2) Manual cutting: residual trees of d.b.h. (diameter at breast height, 4.5 feet above ground) > 1 inch were cut with a chainsaw (August 1981).
- (3) Shear-chop: residual trees were sheared with a KG blade, and debris was masticated with a rotary chopper (September and November 1981).

- (4) Shear-chop-hexazinone: treatment 3 plus application of hexazinone herbicide (Velpar (TM) Gridball pellets) at 2.5 pounds of active ingredient per acre (March 1982). Heavy rains soon after application accelerated herbicide spread and uptake, resulting in subsequent first-year mortality of approximately 35 percent of the planted pines and an 80 percent reduction in first-year cover of associated woody and herbaceous species (Edwards 1994).
- (5) Shear-root rake-burn-disk: residual trees were sheared, rootstocks were raked into windrows and burned, remaining debris was scattered with a bulldozer blade, and plots were disked with an offset harrow to a depth of 6-8 inches (September and October 1981).
- (6) Shear-root rake-burn-disk-fertilize-sulfometuron: treatment 5 plus a broadcast application of ammonium-nitrate fertilizer at 102 pounds of elemental nitrogen per acre and a banded application of sulfometuron (Oust (TM)) herbicide at 6 ounces of active ingredient per acre (March and April 1983).

Each treatment was replicated five times in a randomized complete-block design. In January and February 1982, 1-0 bareroot seedlings of loblolly pine were hand planted at a spacing of 6 ft x 10 ft. Pines that had died in treatment 4 were replanted with new seedlings of the same stocktype in January and February 1983.

Vegetation Measurements and Statistical Analysis

At the center of each treatment plot, a 0.2-acre measurement plot was located. In fall 1993, 12 years after treatment, d.b.h. (nearest 0.1 inch) and species of hardwood and pine trees were recorded for each stem of d.b.h. > 1 inch rooted within a given measurement plot. Data were separated into categories of planted pines (tagged at planting), volunteer pines (not tagged), and hardwoods. Measurement plot values of stand basal area (BA, square feet per acre) were calculated for each category of trees.

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Stand basal area data were subjected to analysis of variance and the following orthogonal contrasts (95 percent significance level):

- I. Absence versus presence of site preparation: treatment 1 versus the mean of treatments 2-6.
- II. Manual cutting versus mechanical site preparation: treatment 2 versus the mean of treatments 3-6.
- III. Absence versus presence of hexazinone: treatment 3 versus treatment 4.
- IV. Absence versus presence of tillage (i.e., root raking and disking): the mean of treatments 3 and 4 versus the mean of treatments 5 and 6.

Stem frequencies (trees per acre) were plotted against 1-inch d.b.h. classes to illustrate the effects of the site preparation treatments on diameter distributions for each of planted pines, volunteer pines, and hardwoods.

RESULTS AND DISCUSSION

Absence versus Presence of Site Preparation

By removing aboveground portions of residual trees, site preparation reduced hardwood BA to about 36 percent of that observed in clearcut-only plots (fig. 1A). Although some of the site-preparation treatments caused abundant sprouting of the hardwood rootstocks (Harrington and Edwards 1996), planted-pine BA in the presence of site preparation (77 square feet per acre) was about 2.7 times that found in the absence of site preparation (28 square feet per acre). Diameter distributions reveal that, in the absence of site preparation, a relatively low density of large, residual hardwoods (31 stems per acre of d.b.h. 6 inches and greater) appear to have limited planted-pine BA (figs. 1B-1C).

Manual Cutting versus Mechanical Site Preparation

Volunteer-pine BA following manual cutting (96 square feet per acre) was over three times the mean value observed for mechanical treatments (30 square feet per acre) (fig. 2A). Apparently in response to severe competition from volunteer pines, planted-pine BA following manual cutting (35 square feet per acre) was about 40 percent of that observed for mechanical treatments (87 square feet per acre). We hypothesized that manual cutting released an abundance of volunteer pines that had germinated the year before pine planting (Harrington and Edwards 1996). Because of overstocking, 91 percent of the volunteer pines in the manual-cutting treatment had a d.b.h. less than 6 inches (987 trees per acre) (fig. 2B). As a result of differences in method of site preparation, diameter distributions for planted pines were either positively-skewed (manual cutting) or relatively normal (mechanical site preparation) (figs. 2B-2C).

Absence versus Presence of Hexazinone

The application of hexazinone during site preparation reduced volunteer-pine BA by half, although it did not result

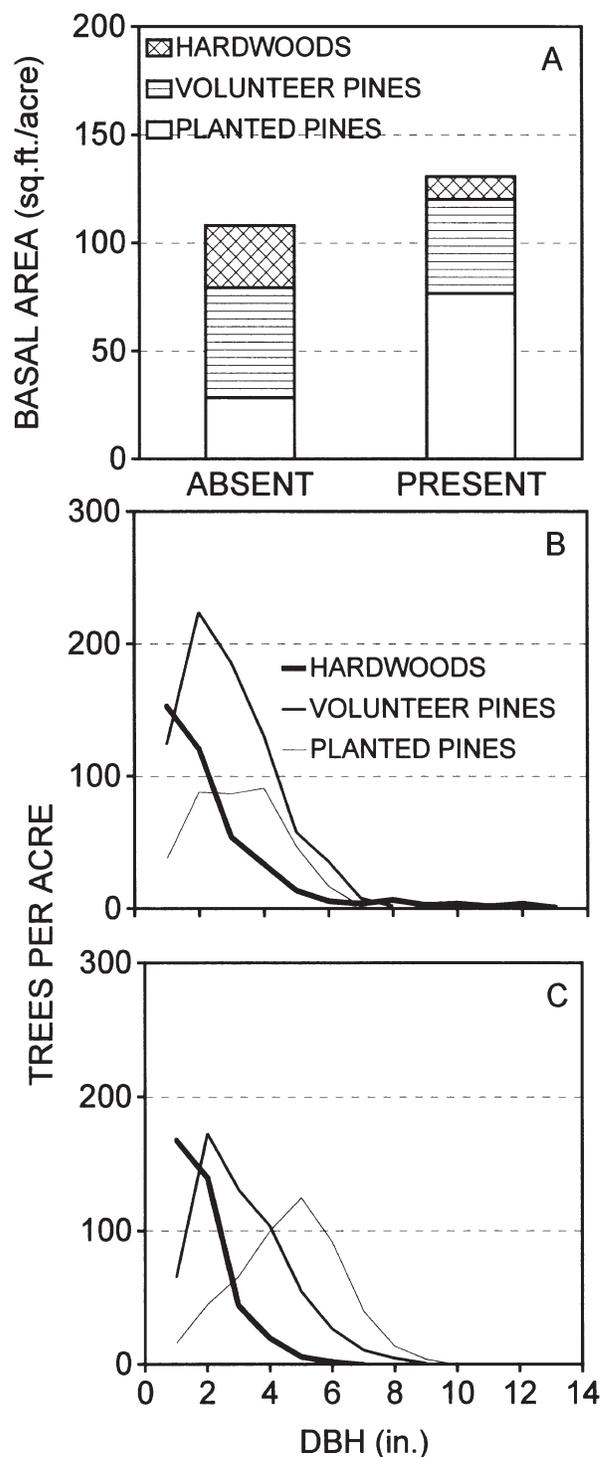


Figure 1—Basal area (A) and diameter distributions of pines and hardwoods 12 years following absence (B) versus presence (C) of site preparation.

in statistically significant effects on BA of planted pines or hardwoods (fig. 3A). Stem density of hardwoods in the presence of hexazinone (192 trees per acre) was about 38 percent of that observed in its absence (511 trees per acre) (figs. 3B-3C). Replanting of pines that died from hexazinone may have resulted in a diameter distribution that was relatively flat and positively skewed, because it

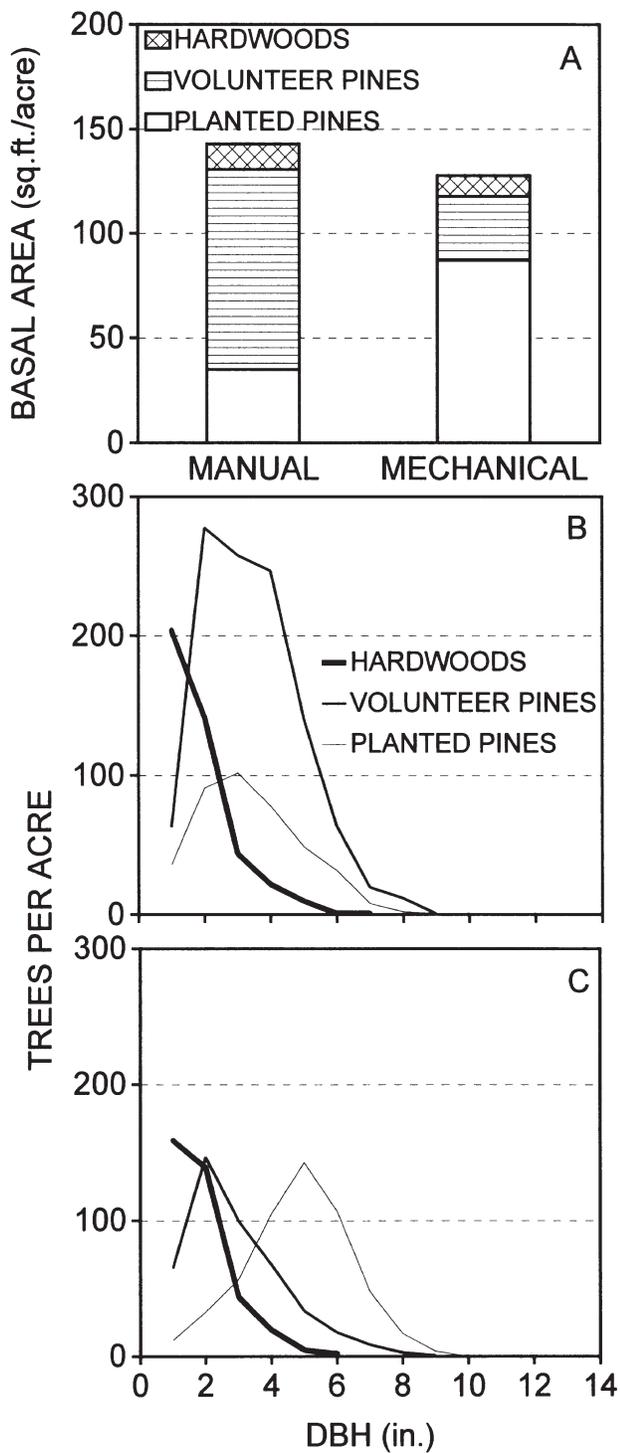


Figure 2—Basal area (A) and diameter distributions of pines and hardwoods 12 years following manual cutting (B) versus mechanical (C) site preparation.

introduced a cohort of seedlings that were a year younger than those of the original planting.

Absence versus Presence of Tillage

Planted-pine BA in the presence of tillage (99 square feet per acre) was about 30 percent greater than that observed in its absence (76 square feet per acre) (fig. 4A). However,

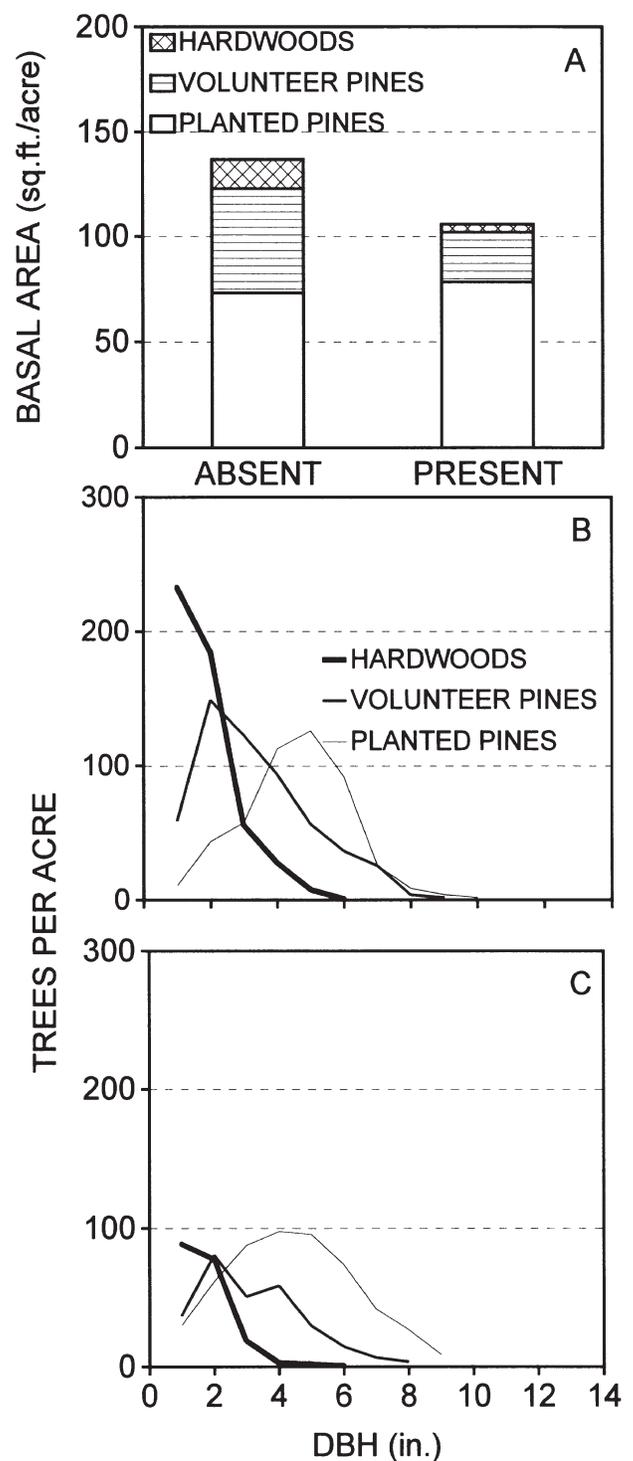


Figure 3—Basal area (A) and diameter distributions of pines and hardwoods 12 years following absence (B) versus presence (C) of hexazinone during site preparation.

basal area of volunteer pines and hardwoods did not differ significantly in the absence versus presence of tillage. From these results, we inferred that increases in planted-pine BA from tillage resulted from improvements in soil characteristics, rather than from a reduction in competing vegetation abundance (Harrington and Edwards 1996). In the second year of the study, Miller and Edwards (1985)

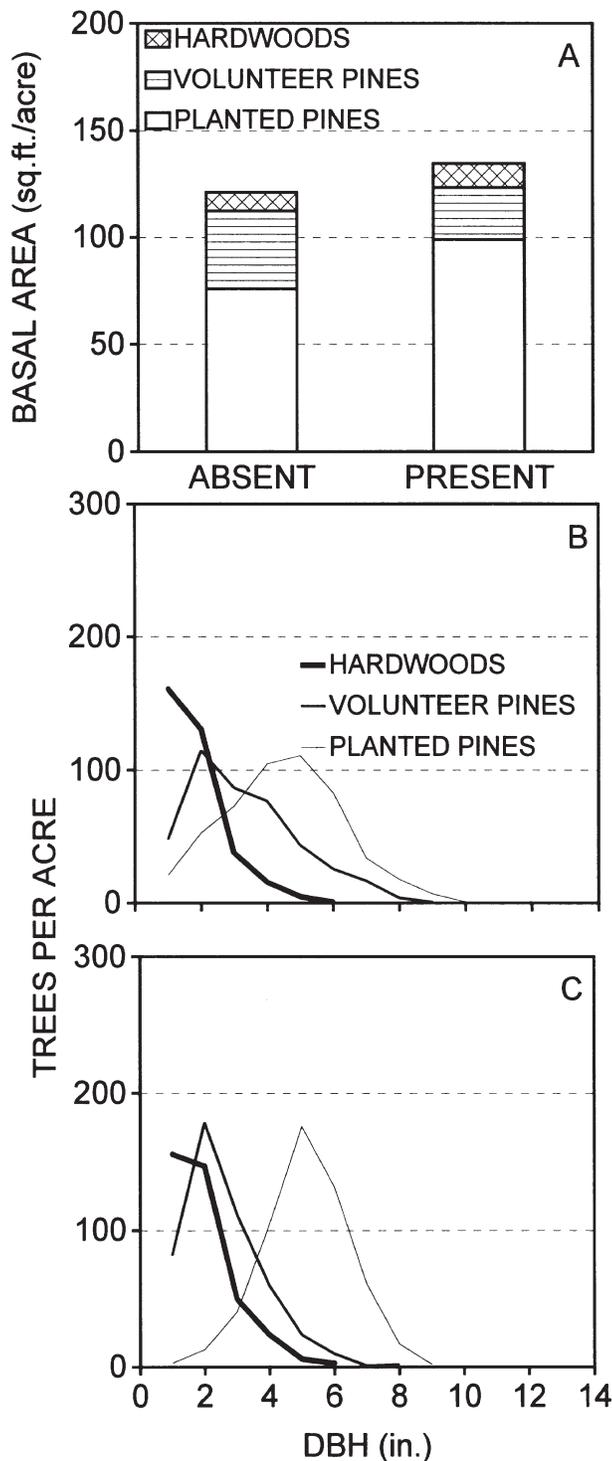


Figure 4—Basal area (A) and diameter distributions of pines and hardwoods 12 years following absence (B) versus presence (C) of tillage during site preparation.

detected reductions in bulk density and increases in pore space following tillage. Presumably because enhanced growing conditions permitted the development of a more uniform stand structure, the normality of the planted-pine diameter distribution was greater in the presence versus absence of tillage (figs. 4B-4C).

CONCLUSIONS

A wide range of stand structures resulted 12 years after various methods and intensities of site preparation. Differences in stand structure resulted because the treatments provided a competitive advantage to either hardwoods, volunteer pines, or planted pines. Absence of site preparation favored residual hardwoods over planted and volunteer pines. Manual cutting released an abundance of volunteer pines from hardwood competition, favoring their dominance over pines planted a year later. Mechanical treatments delayed development of hardwoods and volunteer pines and may have improved soil characteristics—growing conditions that favored the development of productive and uniform stands of planted pine. Results of this research emphasize the importance of understanding how forest disturbances influence subsequent stand development, and how such information can be incorporated into silvicultural systems to better meet stand management objectives.

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STAND DEVELOPMENT 18 YEARS AFTER HARVEST OF A HIGH-QUALITY HARDWOOD SITE ON THE CUMBERLAND PLATEAU IN TENNESSEE

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Abstract—Stand composition and development of a 68-acre, high-quality hardwood site in the Cumberland Plateau Region near Sewanee, TN, has been observed since it was regenerated by clearcutting in 1978. Forty-six permanent plots were established and inventoried prior to harvest, annually through age 5, at age 10, and in 1996, 18 years after harvest. After 18 years, the stand has regained its preharvest basal area of 90 square feet per acre. The stem count (all stems > 4.5 feet) increased from a preharvest level of 1,676 stems per acre, to a peak of 5,204 at age 5, before declining to the current level of 1,970. The number of woody species increased from 31 in the preharvest stand, to 38 at age 10, before dropping to 33 species at age 18. Whereas the six most numerous species prior to harvest were hickories (*Carya* spp.), dogwood (*Cornus florida*), chestnut oak (*Quercus prinus*), blackgum (*Nyssa sylvatica*), ash (*Fraxinus* sp.), and yellow-poplar (*Liriodendron tulipifera*), in descending order, the six most numerous species 18 years after harvest are yellow-poplar, hickories, sugar maple (*Acer saccharum*), chestnut oak, redbud (*Cercis canadensis*), and black locust (*Robinia pseudoacacia*). In each case, the six species compose approximately 60 percent of the total stems present. The largest differences in species densities include increases for yellow-poplar, black locust, and maples (red and sugar), and the dramatic decrease in the population of dogwood, presumably due to dogwood anthracnose. The species composition of the regeneration layer has changed more than that of the larger stems. Oaks, predominately white and chestnut, currently represent the same proportion of total stems as in the preharvest stand, approximately 15 percent. Members of the red oak group contributed only 25 and 18 percent of the oak stems present prior to harvest, and in 1996, respectively. Results indicate that species composition on mesic sites may shift to more shade-intolerant, early successional species after clearcutting, even when all stems > 2 inches d.b.h. are felled and undesirable stems are poisoned. The stand currently has 296 stems per acre judged free-to-grow; 28 percent black locust, 26 percent yellow-poplar, and 15 percent chestnut oak. Yellow-poplar, which was on average 10 feet taller and 1.7 inches larger in diameter than the other two major free-to-grow species, will likely continue to dominate much of the site.

INTRODUCTION

The current study is derived from work initiated in 1978 by the USDA Forest Service in cooperation with the University of the South. Its original purpose was to investigate the potential to predict the future stand composition of a high-quality hardwood site on the Cumberland Plateau from preharvest inventory data.

The species composition of the preharvest overstory and midstory influences later species composition by providing potential stump sprouts and a seed source. The latter is especially true for those species such as yellow-poplar (*Liriodendron tulipifera*) whose seeds remain viable on the forest floor. The preharvest woody seedlings provide advanced regeneration that may grow into the next canopy.

The relationship between post-harvest and preharvest stand composition is dependent upon the degree to which external factors influence species establishment after harvest, as well as the degree to which site conditions are similar to those that gave rise to the original stand. Species in adjacent stands may reduce the influence of the preharvest overstory by contributing seed representing species either not present in the preharvest stand, or present only in small numbers. For example, a model was used to predict stand composition based upon preharvest inventory data, and the predicted composition was compared to the actual composition of the stand 1 year after the harvest. The model greatly underestimated the number of seedlings of pioneer species such as black

locust (*Robinia pseudoacacia*) and yellow-poplar, which were present in moderate to low numbers in the preharvest stand (Waldrop and others 1986). Comparison to other stands indicated that predictions for older stands were frequently better, largely due to the decline in numbers of the pioneer species as the stands aged.

The current objectives of the study are to (1) compare overall stand species composition 18 years after harvest to the preharvest stand composition for woody stems > 4.5 feet tall and woody stems ≤ 4.5 feet tall, (2) identify species for which there have been major increases or decreases relative to the preharvest stand, and (3) observe changes in stand density through time to trace the pattern of stand development following the silvicultural clearcut of a high-quality hardwood site. Since the site used in this study was not matched with a control site, these data provide a case study for the development of high-quality hardwood sites in the Cumberland Plateau Region of Middle Tennessee.

METHODS

Study Area

The 68-acre study area is located in a south-facing cove of the Cumberland Plateau near Sewanee, TN. The cove is bisected by a small stream, Kirby-Smith Branch. The study area consists primarily of north- and south-facing plateau escarpments and upper sandstone slopes and benches, representing landtypes 16 and 17 in Smalley's (1982) land classification of the Mid-Cumberland Plateau. With

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elevations from 1600 to 1800 feet, slopes range from gentle to very steep (>100 percent slope). Much of the area is covered with rocky colluvium. The major soils include Grimsly, Bouldin, and Jefferson and site index estimates (base age 50) for yellow-poplar average 101.

The preharvest stand was two-layered. The older, upper layer consisted of trees ranging from 65 to 140 years in age. The average diameter of the 1675 merchantable trees (≥ 12 inches d.b.h.) that were marked for harvest was 16.5 inches. The trees were 90 percent chestnut oak, hickory, white oak, northern red oak, and yellow-poplar, in descending order. The same five species composed 90 percent of the 1,149 nonmerchantable trees (8 to 12 inches, and a few large culls) on the site. The major difference in the smaller trees was that the hickories and yellow-poplar each moved up 1 in the relative ranking. A large component of the smaller yellow-poplar were poles that originated from a partial harvest 25 years earlier. Stand basal area was approximately 90 square feet per acre. Reproduction of desirable species was generally sparse (fig. 3B), and the stand had closed to the extent that very few plots contained yellow-poplar seedlings less than 4.5 feet.

Experimental Design

In 1978, prior to harvest, 46 permanent plots were established across the study area. The plots were spaced 200 feet apart along a north-south, east-west grid. Each plot consisted of nested 0.01- and 0.001-acre circular plots.

The plots were inventoried prior to harvest, at 1-year intervals through age 5, in 1988 at age 10, and in 1996 at age 18. Data for all measurements prior to 1996 were obtained from the USDA Forest Service, which initiated the study in cooperation with the University of the South.

At each measurement period all stems > 4.5 feet tall within the 0.01-acre plots were tallied by species and classified as free-to-grow (FTG) or overtopped. Stems were judged FTG if they were in the codominant or dominant canopy layer. All stems ≤ 4.5 feet tall within the 0.001-acre plots were tallied by species. In addition, the d.b.h. and height were measured for the dominant tree in each of the four cardinal quadrants of the 0.01-acre plots.

In 1996, the 0.01-acre plots were expanded to 0.02 acres to accommodate the larger tree sizes. D.b.h. was measured on all stems > 4.5 feet tall tallied within the 0.02-acre plots. To facilitate comparison to past data, trees belonging in the original 0.01-acre plot were identified on the tally sheet.

Pre- and Post-Harvest Treatments

Prior to logging, grapevines were severed near groundline and the stumps were treated with Tordon™ 101. Small stems (2 to 8 inches d.b.h.) of undesirable species [dogwood, sourwood (*Oxydendrum arboreum*), red maple (*Acer rubrum*), blackgum, and a portion of the hickories] were also injected.

All stems > 8 inches d.b.h. were harvested by conventional logging methods in the spring and summer of 1978.

Approximately 4,700 merchantable board feet per acre (International Rule) were removed in a total of 1,676 stems. An additional 1,149 nonmerchantable stems > 8 inches d.b.h. were cut by the loggers.

After the harvest, small stems (2 to 8 inches d.b.h.) of desirable species were felled but were not poisoned. A small clump of pole size yellow-poplar were left standing near the creek. These stems were identified as residuals in later inventories and were excluded from plot measurements.

RESULTS

The stand currently contains 18 percent more stems per acre > 4.5 feet and 56 percent less stems per acre ≤ 4.5 feet than did the preharvest stand. After harvest the number of stems > 4.5 feet increased from a preharvest level of 1,676 stems per acre to a peak of 5,226 in 1983 (5 years after harvest) before declining to the current level of 1,970 stems per acre (fig. 1A). The number of stems ≤ 4.5 feet increased from a preharvest level of 6,000 stems per acre to a peak of 23,670 in 1980 (2 years after harvest) before declining to the current density of 2,644 stems per acre (fig. 1B). Stand basal area has regained its the preharvest level of 90 square feet per acre.

Stand closure occurred within 5-10 years of harvest. Densities for individual species generally peaked within 5 years of harvest. Only four species present 10 years after harvest (representing 17 stems per acre) had not become established within 5 years of harvest.

Two different development patterns are apparent among the four most common species in the stand 18 years after harvest (fig. 2). Black locust and yellow-poplar each proliferated and grew rapidly into the canopy, peaked within

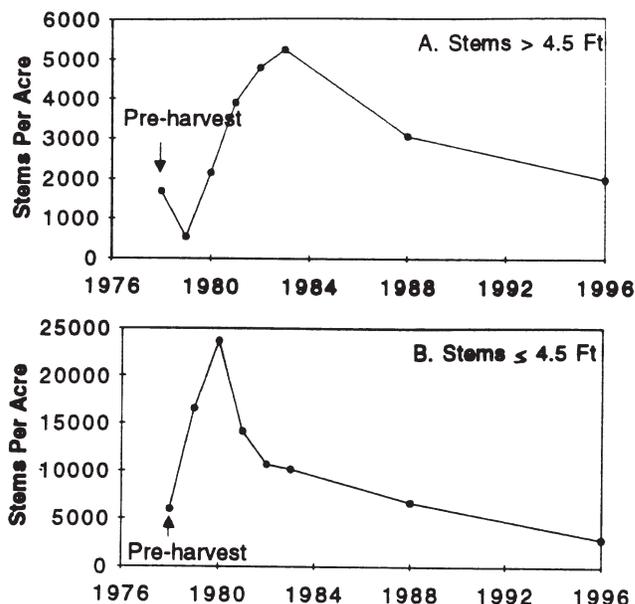


Figure 1—Stand density changes 18 years following harvest. (A) All stems > 4.5 feet tall. (B) All stems ≤ 4.5 feet tall.

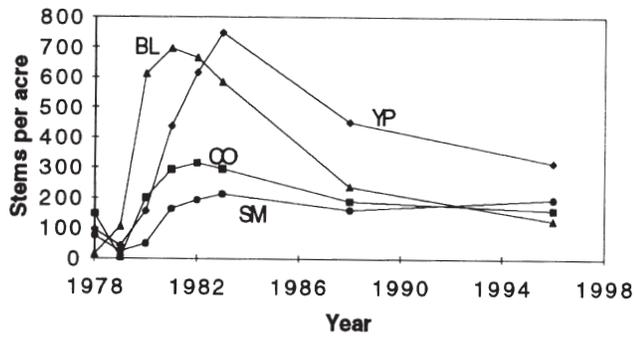


Figure 2—Species density changes for the four most numerous species 18 years after harvest (stems > 4.5 feet). YP = yellow-poplar, BL = black locust, CO = chestnut oak, SM = sugar maple.

3 years, and then began a rapid decline in stems as competition increased and the stand entered the stem exclusion stage of stand development (Oliver and Larson 1996). Eighty-two percent of the young black locust (570 SPA) and 58 percent of the yellow-poplar (433 SPA) died by age 18. Sugar maple produced fewer total stems than either black locust or yellow-poplar, but also exhibited lower mortality (8 percent or 17 SPA). The pattern in chestnut oak was somewhat intermediate (49 percent, or 154 SPA died). The difference in mortality closely mirrors the shade tolerance of the species, with black locust very intolerant, yellow-poplar intolerant, chestnut oak intermediate, and sugar maple tolerant.

The species composition of stems > 4.5 feet is generally similar to that of the preharvest stand. Six of the nine most common species prior to harvest are also among the most common species 18 years later (fig. 3A). Species composing 5 or more percent of the stand prior to harvest

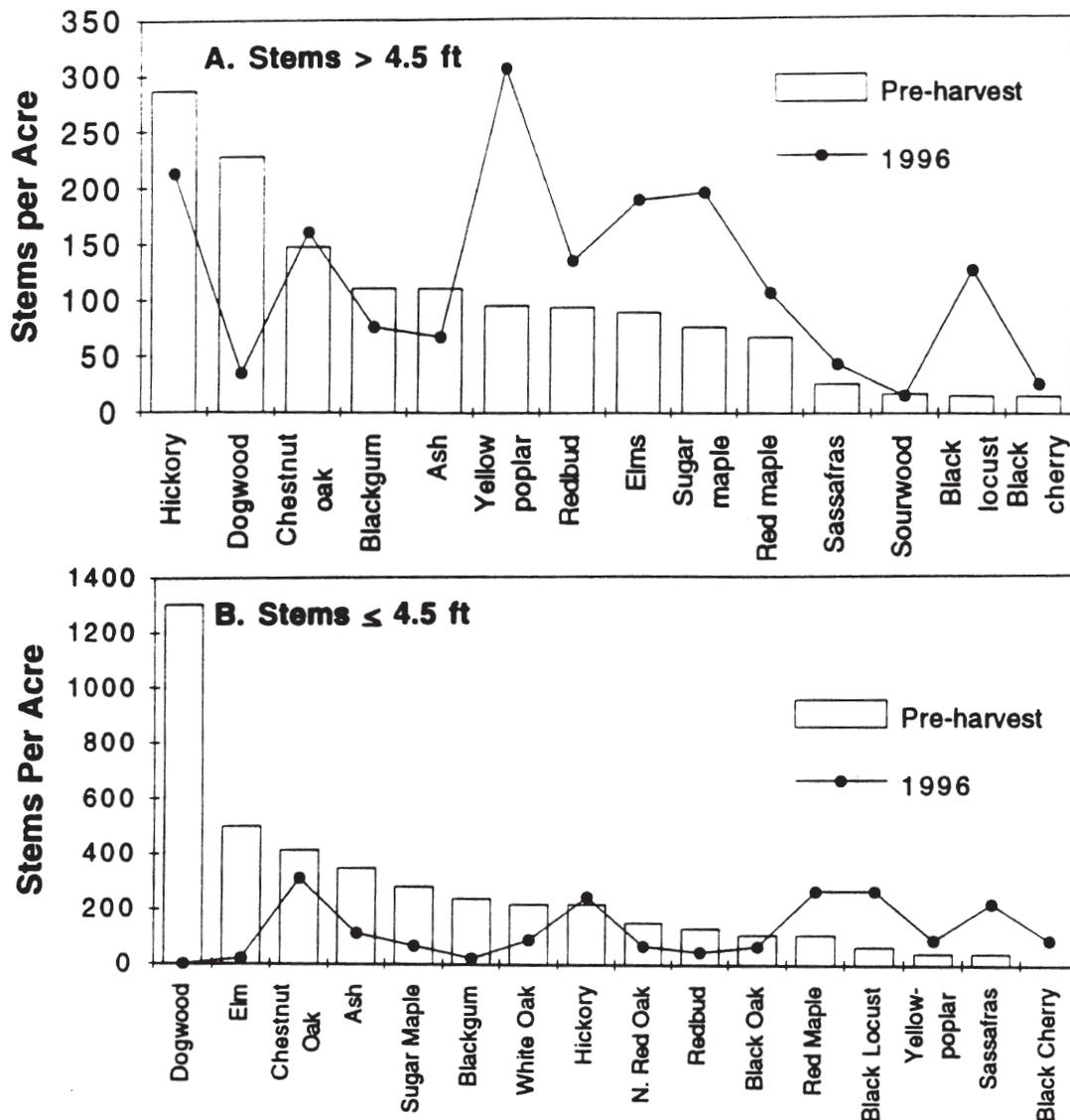


Figure 3—Comparison of pre- and post-harvest density by species. (A) All stems > 4.5 feet tall. (B) All stems ≤ 4.5 feet tall.

were, in descending order, hickories, dogwood, chestnut oak, blackgum, ash, yellow-poplar, redbud, slippery elm (*Ulmus rubra*), and sugar maple. Together these species composed 75 percent of the total stems > 4.5 feet tall. Species composing 5 or more percent of the current stand are yellow-poplar, hickories, sugar maple, chestnut oak, redbud, black locust, red maple, and slippery elm. Together these species compose 70 percent of the total stems.

Species composition of the smaller stems has changed more than that of the larger stems (fig. 3B). The five most common understory species prior to harvest were dogwood (31 percent of stems ≤ 4.5 feet), slippery elm, chestnut oak, ash, and sugar maple. Combined, these species made up 68 percent of the small stems. Only one of the five most common species in 1996, chestnut oak, was a significant component of the preharvest regeneration layer. Hickory, red maple, black locust, and sassafras (*Sassafras albidum*), which currently constitute 50 percent of the stems ≤ 4.5 feet, only contributed 10 percent of the preharvest small stems.

Five species have changed more than 5 percent as a proportion of total stems (> 4.5 feet) per acre. The three species that increased more than 5 percent include yellow-poplar, with a 10 percent increase (6 to 16 percent of all stems), and black locust (1 to 6 percent) and sugar maple (5 to 10 percent), each with a 5 percent increase. The two species groups that exhibited substantial decreases include dogwood with a decrease of 12 percent (14 to 2 percent of all stems), and hickories (*Carya* spp.) with a decrease of 6 percent (17 to 11 percent). With the exception of those species that were only present in 1978 or 1996, all other species are within 5 percent of their preharvest percentages of total number of stems per acre.

The current number of woody species is slightly higher than its preharvest level. Thirty-one woody species were distributed across the 46 plots in the preharvest stand, while 34 species were identified 18 years after harvest. The largest number of species (38) was found 10 years after harvest. Twenty-four species were common to both the pre- and post-harvest stand, while seven species were found in 1978 but not in 1996, and 9 were found in 1996 but not in 1978 (table 1).

Managers of eastern hardwood forests are greatly interested in maintaining or increasing the number of oaks present after a harvest. At the Kirby-Smith site, oaks make up the same percentage of total stems in 1996 that they did prior to harvest (15 percent). Since there are a greater number of total SPA, the actual number of oak stems increased slightly from 256 to 300 SPA. The majority of the oaks (73 percent), are in the white oak group (fig. 4). This represents a slight decline from the 82 percent present prior to harvest. Chestnut oak is the most common oak.

Seventy percent of the current free-to-grow (FTG) basal area is made up of three species: yellow-poplar (45 percent), black locust (16 percent), and chestnut oak (11 percent). This represents 76, 83, and 43 SPA, respectively

(fig. 5). All oaks combined represent 20 percent of all FTG stems, primarily due to chestnut oak, with 15 percent. Seventy-six percent of the 0.01-acre plots (35 of 46) contained an FTG stem of a desirable species (yellow-poplar, oak, black cherry, ash). Only 35 percent of the plots had an FTG oak stem. FTG yellow-poplar stems are on average 12 feet taller and 2 inches larger in diameter than the other FTG species in the study area (fig. 6).

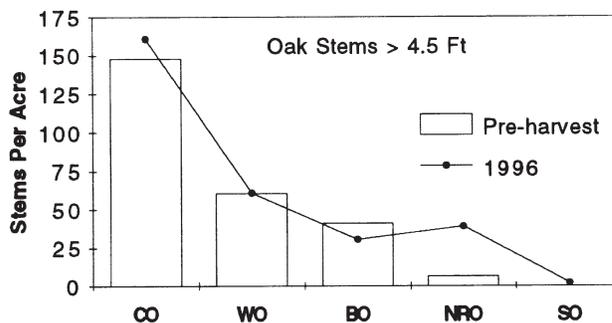


Figure 4—Comparison of pre- and post-harvest oak density by species. CO = chestnut oak, WO = white oak, BO = black oak, NRO = northern red oak, SO = scarlet

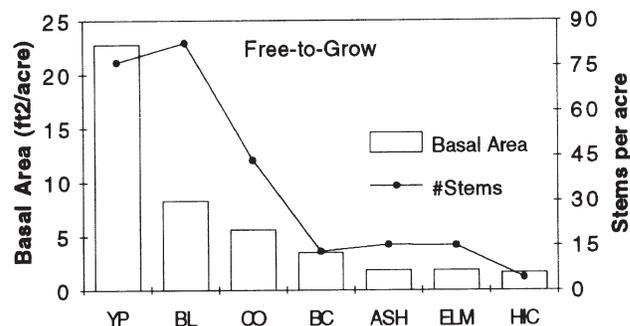


Figure 5—Basal area and density of the stems judged free-to-grow 18 years after harvest. YP = yellow-poplar, BL = black locust, CO = chestnut oak, BC = black cherry, HIC = hickory.

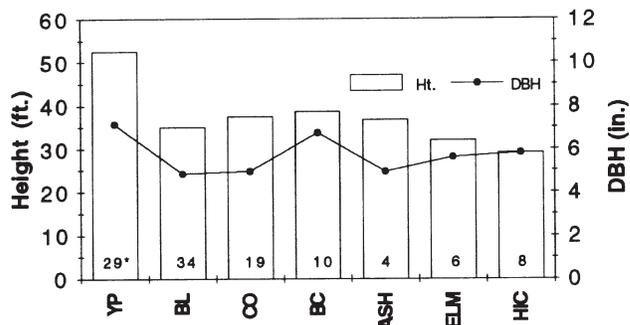


Figure 6—Height and diameter of the stems judged free-to-grow 18 years after harvest (* = number of stems used in the height average; abbreviations are the same as in figure 5).

Table 1—Differences in woody species composition between the preharvest inventory and 10 and 18 years after a silvicultural clearcut

Common name	Scientific name	1978 (Preharvest)	1988	1996
American chestnut	<i>Castanea dentata</i>	*	*	
Ash	<i>Fraxinus</i> (spp)	X	X	X
Azalea	<i>Rhododendron</i> (spp)	X	X	X
Blackhaw	<i>Viburnum rufidulum</i>	X	X	*
Black cherry	<i>Prunus serotina</i>	X	X	X
Blackgum	<i>Nyssa sylvatica</i>	X	X	X
Black locust	<i>Robinia pseudoacacia</i>	X	X	X
Black Walnut	<i>Juglans nigra</i>	*		
Bladdernut	<i>Staphylea trifolia</i>	X		
Blueberry	<i>Vaccinium</i> (spp)	*	X	*
Carolina buckthorn	<i>Rhamnus caroliniana</i>	X		
Dogwood	<i>Cornus florida</i>	X	X	X
Eastern redcedar	<i>Juniperus virginiana</i>	*	*	
Elm, slippery	<i>Ulmus rubra</i>	X	X	X
Elm, winged	<i>U. alata</i>		X	X
Hackberry	<i>Celtis occidentalis</i>		*	*
Hawthorn	<i>Crataegus</i> (spp)	*		
Hickory	<i>Carya</i> (spp)	X	X	X
Hophornbeam	<i>Ostrya virginiana</i>			*
Hydrangea	<i>Hydrangea arborescens</i>	*	X	
Magnolia, cucumber	<i>Magnolia acuminata</i>	*	*	*
Maple, red	<i>Acer rubrum</i>	X	X	X
Maple, sugar	<i>A. saccharum</i>	X	X	X
Mountain laurel	<i>Kalmia latifolia</i>	X	X	X
Mulberry, red	<i>Morus rubra</i>		*	
Oak, black	<i>Quercus velutina</i>	X	X	X
Oak, chestnut	<i>Q. prinus</i>	X	X	X
Oak, chinquapin	<i>Q. muehlenbergii</i>		*	*
Oak, northern red	<i>Q. rubra</i>	*	X	X
Oak, scarlet	<i>Q. coccinea</i>		*	*
Oak, white	<i>Q. alba</i>	X	X	X
Persimmon	<i>Diospyros virginiana</i>	X	X	
Plum	<i>Prunus</i> (spp)		X	*
Rose, multiflora	<i>Rosa multiflora</i>			*
Sassafras	<i>Sassafras albidum</i>	X	X	X
Serviceberry	<i>Amelanchiar arborea</i>	*	*	*
Sourwood	<i>Oxydendrum arboreum</i>	X	X	X
Spicebush	<i>Lindera benzoin</i>	X	X	X
Sumac, winged	<i>Rhus copallina</i>		X	
Witch hazel	<i>Hammamelis virginiana</i>		*	*
Yellow-poplar	<i>Liriodendron tulipifera</i>	X	X	X

* = species represented by fewer than 10 stems per acre.

CONCLUSIONS

The Kirby-Smith site progressed rapidly through the stand initiation stage and is now exhibiting the intense competition characteristics of the stem exclusion stage of stand development. Crown closure occurred between 5 and 10 years after harvest. The number of stems per acre peaked 2 years after harvest, and the greatest mortality

occurred both in large and small stems between ages 5 and 10 (figs. 1A and 1B). The rapid rate of crown closure is characteristic of high-quality sites such as the one in this study. Rapid crown closure will tend to shift species composition of the next stand to species that can become established quickly after disturbance (fast growing, light-seeded species and species with seed in place) and

species with a good complement of advanced regeneration and potential stump sprouts present at the time of harvest.

Although the species composition 18 years after harvest is generally similar to that of the preharvest stand, some differences are apparent. The most significant differences are the large increase in yellow-poplar, black locust, and sugar maple, the reduction in hickory, and the dramatic decreases in dogwood. The increases in yellow-poplar and black locust are not surprising given that both are rapid growing, shade-intolerant species with seeds that are easily dispersed from surrounding stands. In addition, black locust produces prolific root sprouts and yellow-poplar sprouts easily from stumps. Yellow-poplar has the added advantage of developing from seed stored 4 to 7 years in the forest floor (Burns and Honkala 1990). The increases in sugar maple are best explained by the combined release of the advanced regeneration and sprouts arising from small stems cut at harvest. (Sugar maple was the fifth most common species in the regeneration layer prior to harvest.) Declines in hickory are likely due both to their slow growth rate and the poisoning of some stems prior to harvest. While the number of hickories > 4.5 feet has declined, the number of hickory stems \leq 4.5 feet is slightly higher than it was prior to harvest, and it is likely that the number of stems > 4.5 feet will continue to increase as the relatively shade tolerant hickories [mostly shagbark (*Carya ovata*) and pignut (*Carya glabra*)] slowly grow upward toward the canopy.

Dogwood has been virtually eliminated in the stand, and across much of the Cumberland Plateau in the vicinity of Sewanee, as a result of dogwood anthracnose. Whereas 31 percent of the preharvest stems \leq 4.5 feet were dogwood, no dogwood reproduction was present on any plot in 1996. (In the 1988 inventory, 14 percent of the 6,674 stems/acre \leq 4.5 feet were dogwoods.) It is possible that part of the explanation for the increase in red and sugar maple is due to the decline in dogwood, but it is unlikely to be the major factor as the decline has primarily occurred within the past 5-8 years.

The best indicator of the future development of the stand is the composition of the FTG stems. Yellow-poplar, which occupies the greatest basal area and is generally taller than the other FTG stems, will likely retain its dominance over much of the site. Black locust is classified as very intolerant of shade and seldom remains in a closed stand unless it is a dominant tree (Burns and Honkala 1990). Within 10 years after clearcutting a high-quality hardwood site in the Southern Appalachians, black locust numbers had begun to decline, even though it remained the most abundant species on the site (McGee and Hooper 1975). Black locust was the most common species in this study for the first 4 years of the study, but by age 5 it had already begun to decline (fig. 2). Yellow-poplar continued to increase through age 5, and it remains the most common species on the site after 18 years. It can be expected that the black locust will continue to decline with time due to yellow-poplar's current height advantage.

The oak component of the future stand is still in question. The Kirby-Smith site is in a south-facing cove, and much of it is covered with rocky colluvium. Since chestnut oak is favored by the somewhat drier conditions characteristic of a south- rather than north-facing slope, and appears to thrive on very rocky slopes (Foley 1903), it may retain its current level in the stand. While it may grow into positions occupied by declining black locust, it is not likely to replace the taller yellow-poplar in the near future. In a study of mixed upland stands, O'Hara (1986) found that yellow-poplar was able to maintain its dominance over oak and hickory for at least 80 years on sites with a yellow-poplar site index of at least 65 feet (base age 50). Since this study site has a yellow-poplar site index of 101, it is likely that yellow-poplar can maintain its dominance even longer. The red oaks, which only constitute 18 percent of the oak stems present, and 3 percent of all FTG stems, are not likely to contribute much to this stand for a very long time, if at all.

It should be pointed out that the nature of the harvest, in which all stems greater than 2 inches d.b.h. were felled, and the preharvest treatment that poisoned vines and a portion of the undesirable species, also contributed to the current stand composition. The partial harvest 25 years before the study began also played a role. The earlier harvest had resulted in a layer of smaller stems beneath the main canopy. The sprouts from those stems would have contributed to the regeneration after the 1978 harvest. With the tendency for smaller stems to sprout more consistently than larger stems for oaks and many other species (Johnson 1993), the smaller stems may have had a greater influence on the current stand than did the dominant canopy. From the current encroachment of vines, it is also likely that much of the regeneration would have been suppressed if the vines had not been controlled.

The results of this study support the findings of others (e.g., Smith and Ashton 1993; McGee and Hooper 1975) that clearcutting on mesic sites leads to an increase in early successional species such as yellow-poplar and black locust. Regeneration of the later successional species on these sites is dependent upon the presence of advanced regeneration at the time of harvest. Shelterwood cuts that retain enough shade to prevent the establishment of shade intolerant seedlings while allowing advanced regeneration of oaks and later successional species to develop, may be necessary to prevent the domination of mesic sites by species such as yellow-poplar and black locust (Loftis 1990a). Evidence indicates that red oak success on high-quality sites is especially dependent upon advanced regeneration (Loftis 1990b). The partial cut 25 years prior to the 1978 harvest in this study may have provided an environment somewhat similar to that of a shelterwood cut, allowing the development of small chestnut oak seedlings. Ten percent of the regeneration present prior to the 1978 harvest was chestnut oak, and that likely contributed to the current success of chestnut oak on the site.

It is unfortunate that there is not a true control stand to which these data can be compared. Nonetheless, this study site, along with other regional permanent plots, can provide

valuable information concerning long-term stand dynamics in response to harvest. The site has already been used in the validation of the early predictions of FORCAT, a single tree model of stand dynamics (Waldrop and others 1986), and has the potential to serve as a similar test for later stages of stand development.

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STAND DENSITY INDEX FOR SHORTLEAF PINE (*Pinus echinata* Mill.) NATURAL STANDS

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Abstract—Plots located in dense, unthinned, naturally occurring shortleaf pine stands were used to estimate parameters in Reineke's formulation of the maximum size-density relationship between the logarithm (base 10) of number of trees per acre and the logarithm of quadratic mean tree diameter. A first-difference form of the equation was fitted to the remeasured plot data due to autocorrelation in the ordinary least squares residuals arising from repeated annual measurements of plots. Twice the root mean square error was added to the intercept term in the equation since the maximum size-density relationship should lie above the mean relationship for the plot data. The estimated maximum size-density relationship was: $\log(N) = 4.3772 - 1.6863(\log(D))$, where N is the number of trees per acre and D is the quadratic mean diameter (inches). The maximum stand density index implied by this relationship is 491 trees per acre for a stand having a quadratic mean diameter of 10 inches. From this relationship, equations relating maximum basal area per acre to both quadratic mean diameter and number of trees per acre were derived. The maximum basal area per acre relationship implied by the maximum size-density relationship was plotted on the stocking chart of Rogers (1983) together with lines representing 60 percent and 35 percent of the maximum. The curvature of these lines was flatter than the curvature of lines representing equivalent stand density in the Rogers stocking chart.

INTRODUCTION

Management of growing stock levels and manipulation of stand density is a concern of forest managers attempting to satisfy specific management objectives. Determining appropriate levels of growing stock at the stand level is complex because it involves biological, technological, and economic factors specific to each stand (Davis and Johnson 1987). Ideally, individual trees are allocated enough growing space to grow well while not adversely affecting total stand yield.

It is important to distinguish between density and stocking. Density is a measure of the amount of tree vegetation per unit area, while stocking is the relation of any such measure of density to a desired density for a particular objective expressed in the same units (Smith 1986). Forest managers typically measure density of a stand and then are faced with the question: What does the measured density represent relative to an appropriate stocking level in view of management objectives?

Reineke (1933) found the relationship of quadratic mean diameter to number of trees per acre to be very predictable in dense stands experiencing mortality due to competition. This relationship is as follows:

$$\log(N) = b_0 + b_1 \log(D) \quad (1)$$

when

N is the number of trees per acre,

D is the quadratic mean diameter (diameter at breast height of a tree with the average basal area),

$\log(X)$ is the base 10 logarithm of X, and

b_0 and b_1 are coefficients to be estimated.

Reineke (1933) found b_1 , the slope of the line representing the log of number of trees plotted over log of quadratic mean diameter, to be -1.605 for several coniferous species. This relationship, usually using mass as the measure of plant size, has been termed the "self-thinning rule" in the ecological literature (Yoda and others 1963). Reineke used this relationship to develop a stand density index (SDI) by converting stand density to an equivalent value with a standardized average diameter of 10 inches, i.e., SDI is the number of trees per acre if the average stand diameter were 10 inches or:

$$SDI = \log(N) = b_0 + b_1 \log(10). \quad (2)$$

Although Reineke's (1933) concept was first reported over 50 years ago, it appears to have received the most attention in recent years. Stand density management guides for a number of species based on SDI have been developed (Dean and Baldwin 1993, Long 1985, Williams 1994). The general approach defines various key stand density conditions, such as crown closure, the lower limit of self thinning, and full site occupancy as a percentage of the maximum SDI for the species. Thus, it is necessary to have a reliable estimate of the maximum SDI if one wishes to use this approach to develop density management guidelines (Daniel and others 1979).

Comparison of the maximum SDI for various species is also of interest from an ecophysiological viewpoint—pure stands of shade tolerant species experiencing competition-induced mortality might be expected to exhibit higher maximum SDI values than stands composed of intolerants. California-red fir (*Abies magnifica* A. Murr.) and redwood [*Sequoia Sempervirens* (D. Don) Endl.] stands with stand density indexes of 1000 have been found; Douglas fir [*Pseudotsuga menziesii* (Mirb. Franco)] had an SDI of 595; loblolly pine (*Pinus taeda* L.) 450, and longleaf pine (*P.*

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palustris Mill.) 400 (Reineke 1933). Recently, Williams (1996) reported a maximum SDI of 400 for loblolly pine.

The objective of this study was to estimate the maximum SDI for shortleaf pine. The slope of the “self-thinning” line for this species is also of particular interest; Reineke (1933) reported the slope to be steeper than the -1.605 found for several other conifers. Additionally, Zeide (1987) examined data for four *Pinus* and *Picea* species and disputed the assumption of a straight line relationship or constant rate of self thinning. Zeide suggested the line depicting tree size, measured as volume, over tree numbers on a log-log scale is a curve as the rate changes with tree age, species, site quality, and other factors.

METHODS

Study Area

The two study sites are located on industrial forest lands in the Ouachita Mountains of Pushmataha County, OK. Site One is located about 35 miles northwest of Site Two and is within about 25 miles of the western limit of the natural range of shortleaf pine (Lawson 1990). The USDA SCS Soil Survey (Bain and Watterson 1979) includes this site in the Carnasaw-Pirum-Clebit soils association. Measured site index at base age 50 averages 57 ft according to the polymorphic site index curves prepared by Graney and Burkhart (1973). Site Two soil is mapped in the Sherwood-Zafra association (Bain and Watterson 1979). Measured site index at 50 years averaged 73 ft at this site.

Dominant soils at both sites formed in materials weathered from shale and sandstone and are deep and well-drained. The underlying bedrock at Site One is tilted and slope gradients range from 8 to 20 percent, while at Site Two slopes range from 3 to 8 percent (Bain and Watterson 1979). The tilted rock formations result in variable solum thickness within short linear distances, consequently, average soil depth is probably greater at Site Two.

Stand Treatments

A thinning study was installed at Site One in the dormant season prior to the 1989 growing season—stands were 25 to 30 years old at the time (Wittwer and others 1996). Similar thinning treatments were implemented at Site Two 1 year later—these stands were 30 to 37 years old at the time. Three unthinned control plots at each site provide the data for the study reported here. At Site One, measurement plots were 0.10 ac, surrounded by a 33-ft-wide isolation strip. At Site Two, measurement plots were 0.2 ac surrounded by a 33-ft isolation strip. Diameter at breast height of all living trees was measured annually for 8 years at Site One and 7 years at Site Two.

Data Analysis

Data were summarized on an area basis and quadratic mean diameter computed from the observations of number of surviving trees and basal area. Statistical procedures based on linear regression analysis were used to estimate the slope parameter for the relationship between the logarithm of number of trees per acre and the logarithm of

quadratic mean diameter per acre. Results of this analysis were used to estimate a maximum stand (SDI) for shortleaf pine.

RESULTS AND DISCUSSION

The number of trees was greater and quadratic mean diameter and stand basal area less on Site One compared with Site Two (table 1). During the 8-year observation period on Site One, the total number of trees decreased approximately 46 percent, while on Site Two tree numbers decreased about 28 percent during the 7-year observation period. Total basal area was in the range of 200 ft²/ac at the last observation. The steady decrease in the number of trees and very slow increase in stand basal area suggest these data should provide a good estimate of the maximum SDI to be attained by shortleaf pine.

A preliminary estimate of the maximum SDI for shortleaf pine was made, using the slope value of -1.605 found by Reineke (1933) to represent several conifer species (table 1). Estimates did not exhibit an increasing trend, but varied due to random variation in annual mortality rates around a mean of 457 on Site One and 421 on Site Two. Lack of an increasing trend in these annual estimates over several years further suggests these plots are near the maximum SDI for shortleaf pine.

Preliminary estimates of parameters for a linear equation relating the logarithm of number of trees per acre to the logarithm of quadratic mean diameter were made by ordinary least squares (OLS), resulting in an estimate of $b_1 = -1.7686$ for the slope parameter. Annual measurements of trees per acre and quadratic mean diameter were made on each of the plots, so that there were eight measurements at Site One and seven measurements at Site Two. It is well known that autocorrelation from a series of measurements taken in time can result in a violation of the assumption of independent error terms. A standard procedure used to test for autocorrelated error terms is the Durbin-Watson (DW) test (Neter and others 1989). The DW test was performed using the AUTOREG procedure in SAS/ETS (SAS Institute 1993). A DW statistic of 0.2431 with a p-value of 0.0001 resulted, indicating significant autocorrelation. A remedial measure that is frequently used when autocorrelation is present in the OLS residuals is to estimate the slope parameter using the first-difference model. This model is developed as follows:

$$\log(N_t) - \log(N_{t-1}) = b_1\{\log(D_t) - \log(D_{t-1})\} \quad (3)$$

where

N_t is number of trees per acre in year t ,

N_{t-1} is number of trees per acre in year $t-1$,

D_t is quadratic mean diameter in year t , and

D_{t-1} is quadratic mean diameter in year $t-1$.

The intercept parameter is estimated by requiring the average value of $\log(N)$ to satisfy the equation when evaluated at the average value of $\log(D)$. Estimating the

Table 1—Summary statistics for trees per acre, quadratic mean diameter at breast height, basal area, mortality rate, and Stand Density Index (SDI)^a

Site /yr.	Trees per acre			Quad. mean d.b.h.			Basal area			Mortality rate	SDI
	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.		
			----- Inches -----			----- Ft ² /acre -----			Percent		
Site One:											
1	2476	2872	3267	3.0	3.2	3.3	140	158	172	13.3	455
2	2291	2489	2886	3.3	3.4	3.5	143	163	177	10.5	458
3	2059	2227	2580	3.5	3.6	3.8	146	167	180	10.9	455
4	1825	1985	2324	3.8	3.9	4.1	148	169	182	5.0	450
5	1748	1885	2181	4.0	4.1	4.4	154	176	187	6.6	457
6	1553	1760	2124	4.1	4.4	4.7	157	181	195	5.5	460
7	1417	1669	2076	4.2	4.5	4.9	160	184	198	7.3	462
8	1340	1547	1914	4.4	4.7	5.1	161	185	200		457
Site Two:											
1	893	1070	1248	5.4	5.7	6.0	175	186	196	3.4	427
2	863	1033	1196	5.5	5.8	6.2	178	189	199	10.3	430
3	758	927	1062	5.9	6.1	6.5	176	189	199	7.0	421
4	689	862	1006	6.0	6.4	6.8	175	189	200	2.9	415
5	689	837	949	6.2	6.5	6.9	180	193	202	2.4	419
6	674	817	933	6.4	6.7	7.1	183	196	206	6.5	422
7	654	764	872	6.5	6.9	7.2	185	195	203		414

$$^a \text{SDI} = (\text{trees / acre}) \times \left(\frac{\text{quadratic mean dbh}}{10} \right)^{1.605}$$

slope parameter by using the first difference model gives $b_1 = -1.6863$ with standard error of 0.05.

The DW statistic for the residuals from the first difference model was 2.1 with a p-value of 0.64, indicating failure to reject the null hypothesis of no autocorrelation. However, the power of the DW test is very low for models that do not contain an intercept (Judge and others 1988). Neter and others (1989) suggest fitting the first difference model with an intercept solely for the purpose of testing for autocorrelated errors. This procedure resulted in a DW

statistic of 2.0 with a p-value of 0.48, indicating failure to reject the null hypothesis of no autocorrelation. Thus the first-difference model appears to have greatly reduced autocorrelation among error terms.

When the prediction equation for $\log(N)$ is required to pass through the means of the data the following model is obtained:

$$\log(N) = 4.3031 - 1.6863(\log(D)). \quad (4)$$

Fit index = 0.968, Root Mean Square Error (RMSE)=0.03706.

The fit index and RMSE for residuals are based on predictions for $\log(N)$. This slope value is not quite as steep as that obtained by OLS but is still steeper than the Reineke value of -1.605. Reineke (1933) also found that his shortleaf data required a slope steeper than -1.605. Although he did not report the numerical value of the slope for shortleaf, figure 7 in Reineke's 1933 publication implies a slope of approximately -1.85. Thus, the value obtained from the Oklahoma data reported in this study lies between Reineke's general value of -1.605 and the value implied by his shortleaf data.

The maximum size density line should be located "above" the average for fully stocked plots. Thus, the intercept for the equation above was increased by adding twice the RMSE of the residuals ($4.3031 + 2(0.03706)$). The following maximum size-density relationship results:

$$\log(N) = 4.3772 - 1.6863(\log(D)). \quad (5)$$

The maximum size-density line reported above is plotted with the data used for estimation of the slope coefficient in figure 1. From this, an estimate of maximum SDI can be obtained by using this equation to estimate the maximum number of trees per acre associated with a d.b.h. of $D=10$:

$$\text{maximum SDI} = 10^{4.3772-1.6863} = 491. \quad (6)$$

The maximum size-density relationship can be used to establish a relationship between maximum basal area per acre and quadratic mean diameter. Consider the

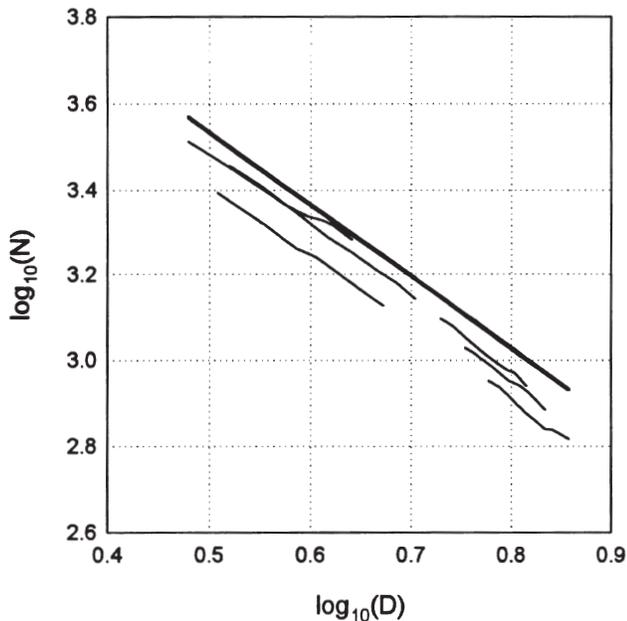


Figure 1—Maximum size-density line of base 10 logarithm of number of trees per acre (N) vs. base 10 logarithm of quadratic mean diameter (D), in inches, for shortleaf pine with even-aged natural stand data used for parameter estimation. Line segments below maximum indicate annual measurements for individual plots.

antilogarithm of both sides of the maximum size density equation:

$$N = aD^b \quad (7)$$

where

$$a = 10^{4.3772}, \text{ and}$$

$$b = -1.6863.$$

To obtain an equation for maximum basal area, multiply both sides of the equation by $0.005454D^2$:

$$0.005454D^2(N) = 0.005454aD^{2+b}. \quad (8)$$

This results in the following equation relating maximum basal area per acre to quadratic mean diameter:

$$B_{\max} = aD^{2+b} \quad (9)$$

where

B_{\max} is maximum basal area per acre.

For the parameter estimates obtained in this study:

$$B_{\max} = 129.9952D^{0.3137}. \quad (10)$$

Note that this implies an increase in maximum basal area per acre with increasing quadratic mean diameter. This trend will occur whenever the absolute value of the slope parameter in the maximum size-density relationship is less than 2. A value of $b = -2$ would imply that maximum basal area per acre is the same for all values of quadratic mean diameter. Figure 2 indicates the relationship between maximum basal area per acre and number of trees per acre.

The maximum size-density relationship can also be used to obtain a relationship between maximum basal area per acre and number of trees per acre. Solving for quadratic mean diameter and squaring both sides gives the following results:

$$(N/a)^{2/b} = D^2$$

$$0.005454N(N/a)^{2/b} = 0.005454ND^2 = B_{\max}. \quad (11)$$

Thus, with algebraic simplification, the following relationship between maximum basal area and number of trees per acre is obtained:

$$B_{\max} = 0.005454(1/a)^{2/b} N^{1+2/b}. \quad (12)$$

For the parameter estimates obtained in this study:

$$B_{\max} = 0.005454(10^{-4.3772})^{-2/1.6863} N^{1-2/1.6863} = 847.6405N^{-0.1860}. \quad (13)$$

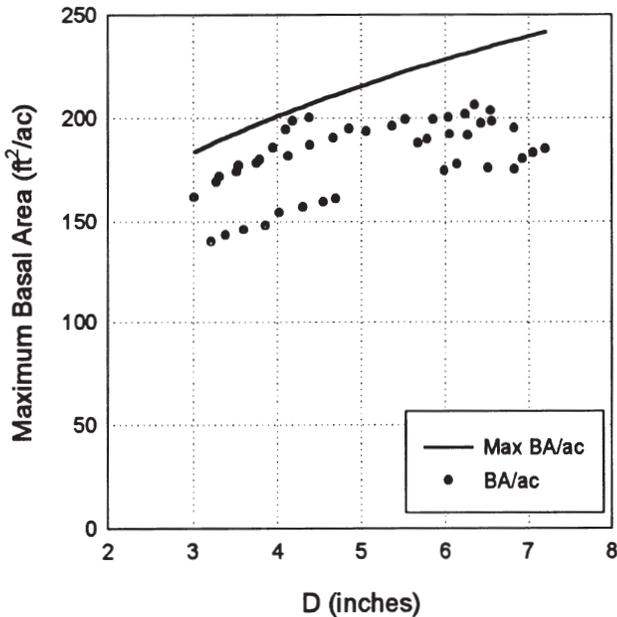


Figure 2—Relationship between maximum basal area per acre and quadratic mean diameter (D) for shortleaf pine with data from even-aged natural shortleaf pine stands.

This indicates that maximum basal area per acre is inversely related to maximum number of trees per acre, and this would be true for all values of $b < -2$. Such a relationship is consistent with the idea that stands having larger quadratic mean diameters have larger basal area per acre, since number of trees per acre is inversely related to tree size. Figure 3 shows the relationship between maximum basal area per acre and number of trees per acre.

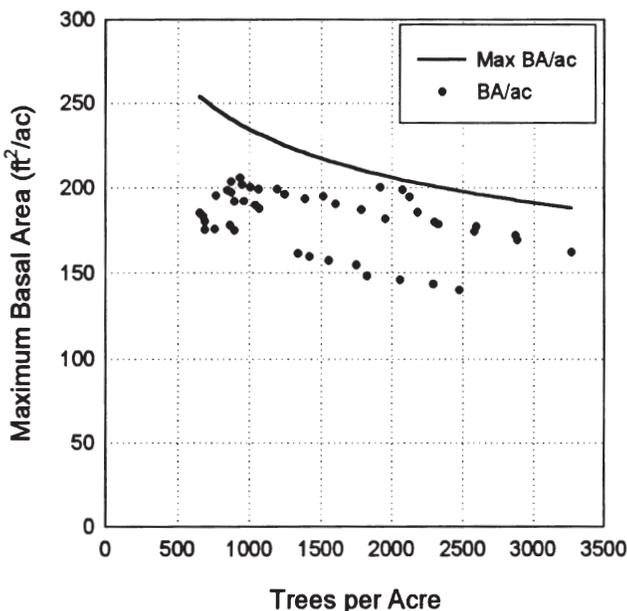


Figure 3—Relationship between maximum basal area per acre and number of trees per acre with data from even-aged natural shortleaf pine stands.

Several authors have used the maximum size-density relationship to develop forest stand density management diagrams (e.g., Williams 1994; Long 1985). Generally, important features of these diagrams include lines drawn parallel to the maximum stand density line which represent stocking levels of significance. Rogers (1983) has developed a stocking chart for shortleaf pine based on the crown competition factor concept (fig. 4). Like the Gingrich (1967) stocking chart for upland central hardwoods, the Rogers (1983) chart is based on basal area per acre (y axis) vs. number of trees per acre (x axis). Kershaw and Fischer (1991) developed a stand density management diagram for upland central hardwoods based on a maximum size-density line relating mean tree volume to maximum number of trees per acre. They commented on the relationship between their diagram and the Gingrich (1967) stocking chart.

Stand density management diagrams based on the Reineke (1933) concept usually indicate regions parallel to the maximum line, which are proportions of maximum density: $pN = (pa)D^b$ where p is proportion of maximum stocking according to the maximum size density relationship between number of trees per acre and quadratic mean diameter per acre. In order to compare Rogers' stocking chart with the density management concept, the following equation was used:

$$B_p = 0.005454(1/(pa))^{2/b} N^{1+2/b} \quad (14)$$

This is based on the equation discussed above, which was derived from the maximum size density relationship. For the parameter estimates obtained in this study, this equation is:

$$B_p = 0.005454(1/(p10^{4.3772}))^{-1.1860} N^{-0.1860} \quad (15)$$

In figure 4, the Rogers chart is presented together with the maximum stocking curve implied by the maximum size-density relationship above ($p=1$). Also included are the 60 percent ($p = 0.6$) and 35 percent ($p = 0.35$) stocking levels based on the maximum size-density relationship. The 60 percent level of maximum size-density is at or near the level often considered to be the "lower limit of self-thinning" in many density management diagrams, while the 35 percent of maximum size-density level is often considered the "lower limit of full-site occupancy" (Long 1985).

Since Rogers' chart is based on the crown competition factor concept of Krajicek and others (1961), it is not necessarily expected to be equivalent to a density management diagram based on the Reineke maximum size-density relationship. Nevertheless, it is of interest to see how the two concepts compare. The Rogers "B: minimum full-stocking" is based on full site occupancy with trees having maximum crown width. Figure 4 helps evaluate these comparisons. The "A: maximum full-stocking" line is maximum stocking based on a minimum growing space requirement allocating individual trees 60 percent of maximum growing space (Rogers 1983). Clearly, the density management diagram lines have a curvature that is different than that on the Rogers stocking chart.

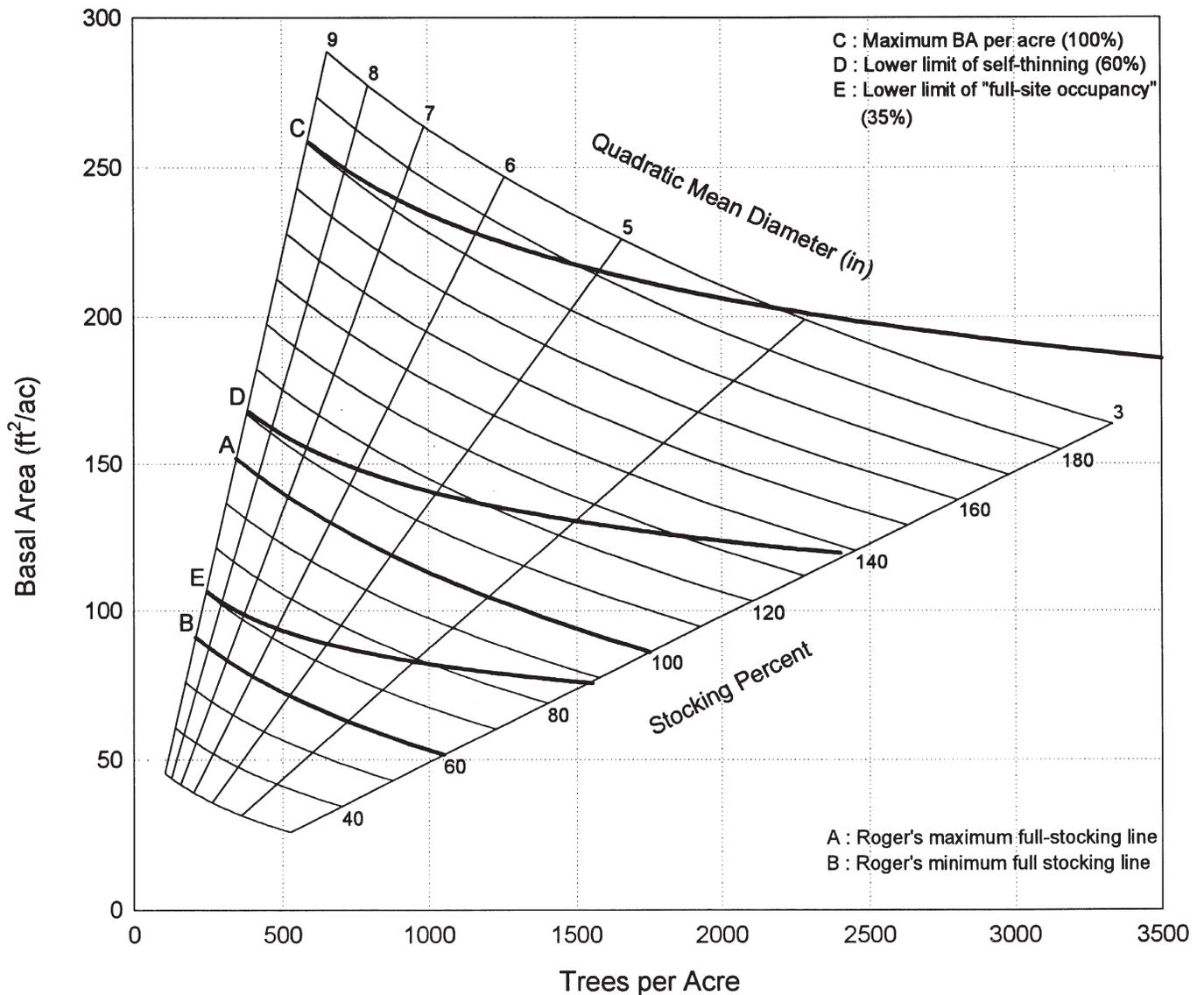


Figure 4—Rogers' (1983) shortleaf pine stocking chart with lines indicating maximum, 60 percent of maximum, and 35 percent of maximum basal area implied by the maximum size-density relationship.

Furthermore, "A" on the Rogers maximum full-stocking line is uniformly lower than the 60 percent maximum size-density line. In a similar way, the Rogers "B" line is lower than the 35 percent maximum size-density line.

The curvature of the lines based on the maximum-size density principle is flatter than lines of constant stocking on the Rogers chart. This means that according to the maximum size-density principle, stands of the same basal area but differing in average diameter are more similar with respect to stocking than they would be according to the Rogers stocking chart. This is not necessarily unexpected because the curvature of the basic equation derived from crown competition factor for the Rogers chart is different than the curvature of the relationship between number of trees per acre and basal area per acre derived from the maximum size-density relationship.

SUMMARY AND CONCLUSIONS

Dense, unthinned plots which were established and remeasured over a 7- to 8-year period in naturally occurring, even-aged shortleaf pine stands were used to estimate the parameters of a maximum size-density relationship of the type used by Reineke (1933) between the logarithm of trees per acre and the logarithm of quadratic mean diameter. Since the plots were measured annually, a Durbin-Watson test was used to test for autocorrelation in the ordinary least squares residuals. Autocorrelation in these residuals was significant, therefore the first-difference equation method was used to estimate the parameters of a size-density relationship for these plots. Finally, a maximum line was estimated by adding twice the root mean square error to the intercept in the size-density relationship obtained for these plots. A slope parameter of -1.6863 was obtained for the relationship between the logarithm of number of trees per acre

(dependent variable) and the logarithm of quadratic mean diameter (independent variable). This value is steeper than the value -1.605 recommended by Reineke for a wide range of species, but not quite as steep as the value Reineke obtained for his shortleaf data.

Evaluation of stand density based on lines parallel to the maximum size-density line was compared to the Rogers (1983) stocking chart for shortleaf pine. The lines representing percentages of the maximum size-density had flatter curvature than lines of equivalent stocking percentages on the Rogers chart. Lines representing the lower limit of self-thinning and the lower limit of full site occupancy according to the maximum size density concept were located at higher levels than the Rogers "A: maximum full-stocking" and Rogers "B: minimum full-stocking" lines, respectively.

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