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Species, spacing and their interactions in four southern pines

David C. Miller

To the Graduate Council:

I am submitting herewith a thesis written by David C. Miller entitled "Species, spacing and their interactions in four southern pines." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Forestry.

John C. Rennie, Major Professor

We have read this thesis and recommend its acceptance:

E. Buckner, J. McLaren, E. Thor

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Vice Chancellor
Graduate Studies and Research

SPECIES, SPACING AND THEIR INTERACTIONS

IN FOUR SOUTHERN PINES

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

David C. Miller

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ABSTRACT

The effect of initial spacing on plantations of loblolly pine (*Pinus taeda*), shortleaf pine (*P. echinata*), Virginia pine (*P. Virginiana*), and eastern white pine (*P. strobus*) in Tennessee is not well understood.

A study of these four pines was established at the Highland Rim Forestry Field Station near Tullahoma, Tennessee. The plantation was laid out in a split plot design with the four species as main plots and four spacings as split plots. The study was measured at age 16 and total height, diameter at breast height, crown radius, height to first remaining branch, height to first live branch, percent live crown, volume per tree, basal area per tree, volume per hectare, and basal area per hectare were analyzed for all species. Number of branches per whorl nearest breast height and diameter of the largest branch in that whorl were analyzed for white pine only. Generally, the trees showed increased growth as spacing widened. Total height showed a significant effect of spacing.

It was concluded that loblolly and white pine are the preferred species for planting.

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INTRODUCTION

The question of optimum initial spacing for plantation grown pines is a controversial one and has been fueled by a lack of conclusive research. Amidst a welter of conflicting advice, the resource manager often makes his decision on planting density without knowing clearly the consequences of his choice. A spacing may be chosen simply because it has been used before or "looks right." This process of decision making can have disastrous effects on the achievement of landowner goals.

Four pines are grown in Tennessee for pulp or timber: *Pinus taeda* L. (loblolly pine), *P. Virginiana* Mill. (Virginia pine), *P. echinata* Mill. (shortleaf pine), and *P. strobus* L. (eastern white pine). The effect of spacing on the last three is not well-documented and only one spacing study aside from the present one has been established in Tennessee (Russell, 1979). Given that initial spacing can have a large influence on the growth behavior of these species, the need for further information is apparent.

Presented in this thesis is a characterization and evaluation of a stand of the four pines named above grown for 16 years at various spacings. The study's goal is to aid resource managers in Tennessee in making plantation spacing decisions. No single spacing regimen can be recommended since the objective of the resource owner must determine the manager's manipulation of the trees and spacing is only one, albeit important, input in stand management. The effect of spacing on several different expressions of growth will be examined for each species at different spacings, the species-spacing interaction, will be explored. Distinctions among species will be based on differences in their ability to produce quality fiber quickly.

CHAPTER I

LITERATURE REVIEW

Introduction

When the decision to establish a pine plantation has been made, the question of stand density must be considered. Stand density is usually thought of in terms of stems per acre or distance between stems. Early American foresters recommended very close spacings advising that, generally, ". . . Trees should not be spaced farther apart than 5 or 6 feet," (Ferguson, 1916). Quick crown closure was desired so that the soil might be protected (Toumey and Korstian, 1931). Modern planting has tended to wider spacings, usually not more than 1,200 trees per acre (6' by 6') and often many fewer (Sharpe, Hendee, and Allen, 1976). The philosophy underlying planting less densely was stated by Linstrom (1960) and was formulated more fully by Smith (1962) as

> . . . optimum yield of utilizable wood and not to maximize gross production in terms of total cubic volume or tonnage. . . . The ideal number of trees to plant is precisely the number that can be grown to the smallest size that can be utilized profitably.

Even in Europe, where smaller trees are utilized, the trend has been to wider spacings (Linstrom, 1963).

Linstrom (1963) recommends eight factors be considered in choosing a plantation spacing: product objectives, thinnings, hazards, growth rates, natural regeneration, branching, species, and planting costs.

These multifarious considerations create a view of a very complex decision. Most recent stand density analyses have subsumed many of these factors under a single heading and has focused on product goals as the major determinant of spacing choice (Goebel, 1974).

The following is a discussion of the effects of spacing on selected tree parameters as they are described in the literature.

Diameter At Breast Height

The most widely and consistently recognized factor affected by initial spacing is that which affects bole diameter. Many researchers have noted that diameter at breast height (dbh) varies directly with increasing width of spacing. This relationship was noted at least as early as the turn of the century (Ferguson, 1916) and has been mentioned in nearly every report since (Stevenson and Bartoo, 1939; Ware and Stahelin, 1948; Russell, 1958; Hansbrough, 1968; and Russell, 1979) in species as diverse as *Pseudotsuga menziesii* (Mirb.) Franco (Douglas-fir) (Reukema, 1959), loblolly pine (Shepard, 1974), *P. elliotii* Engelm (slash pine), Virginia pine (Russell, 1979), *P. banksiana* Lamb. (jack pine) (Ralston, 1953), *P. resinosa* Ait. (red pine) (Lundgren, 1981), and *P. palustris* Mill. (longleaf pine) (Lohrey, 1974). Furthermore, wide spacings will yield higher numbers of trees in the larger and thus more merchantable diameter classes. Mann (1971) found that slash pine planted at 250 trees per acre produced more trees eight inches dbh and larger than did planting rates of 1,150, 1,600, or 2,500 trees per acre.

Logically those trees with greater absolute diameter growth should also show a greater rate of growth than same-aged smaller trees and this effect is confirmed in the literature (Bramble, Cope, and Chisman, 1949). However, there is disagreement concerning the age at which these differential rates operate. In slash pine, Nelson (1952) found dbh depression as early as age three in seedlings spaced 6' by 6' and depression beginning at age six in 12' by 12' plots. Another researcher in slash pine found no significant spacing effects at age four among trees spaced variously from 6' by 6' to 12' by 12' (Worst, 1964). Shepard (1974), studying loblolly pine, found that most of the advantage in diameter growth among wider spacings over narrower ones came in the first 12 years of growth. He observed that the average rates of diameter growth between age 21 and age 25 were the same for all spacings from 4' by 4' to 10' by 10'. Measuring unthinned stands of red pine, Lundgren (1981) found the rate of diameter growth slowing at ages 11-13 for 1,200 trees per acre, 12-15 for 800 trees per acre, and 17-20 for 400 trees per acre. Unimpaired diameter growth was maintained among trees spaced 15' by 15' until age 25.

Improving site quality appears to amplify differences among spacings but only marginally. In loblolly pine, site quality does produce a significant positive effect on dbh but it is less important than spacing (Campbell and Mann, 1974; Mann and Dell, 1971). Owens (1974) reported that production on all spacings increased with site index. Brender (1973) recommended that choice of spacing should be dependent on site quality in order to maintain good diameter growth.

The apparent biological explanation for the marked effect of initial spacing on diameter growth is lateral competition. As spacing narrows, crown interface and root competition begin earlier, reducing each plant's share of available nutrients, moisture and light, thereby slowing growth (Mann and Dell, 1971; Nelson, 1952; Owens, 1974).

Height Growth

A widely accepted early view was that close spacing induced rapid height growth (Ferguson, 1916). No modern research supports that assumption at least among pines, and much contradicts it. For shortleaf pine, loblolly pine, longleaf pine and slash pine no effect of spacing on height has been shown among trees of varying ages up to 35 years (Harms and Collins, 1963; Lohrey, 1974; Owens, 1974; Williams, 1959). However, Balmer, Owens and Jorgenson (1975), Hansbrough (1968), and Shepard (1974) found that loblolly pine showed a slight increase in height as spacing widened. Bennett (1974) and Collins (1967) found the same thing in slash pine. The same effect was reported in red pine (Bramble, Cope and Chisman, 1949) and in Douglas-fir (Reukema, 1959). In two studies on loblolly pine, there were indications that close spacing, even as wide as 6' by 6' at 15 years (Balmer, Owens and Jorgenson, 1976) and certainly as wide as 4' by 4' at 20 years (McClurkin, 1976) actually depressed height growth. Height of trees in these spacings was found significantly lower than on spacings of 6' by 6', 8' by 8' and 12' by 12', while heights of trees in these wider spacings did not differ significantly.

Survival And Volume Production

The volume of wood in a stand is dependent on tree diameters and heights and on the number of stems per unit area. Generally, denser spacing produces more total volume and a greater total basal area (Box, Applequist and Linnartz, 1965; Campbell and Mann, 1974; Echols, 1959; Mann, 1971; Owens, 1974; Ralston, 1953; Russell, 1958; Ware and Stahelin, 1948). Working with Douglas-fir, Reukema (1959) found that basal area actually increased as spacing was widened from 4' by 4' to 12' by 12'. Twenty-five-year-old loblolly pine has produced not only greater basal area but greater total cubic foot volume when planted at 10' by 10' than at narrower spacings down to 4' by 4'. This effect, it was noted, had been expressed only in the last four years of growth and was attributed to heavy mortality in the closer spacings (Shepard, 1974).

Survival obviously affects volume production since it determines the number of trees producing wood. Most studies have indicated that survival increases with widening spacing (McClurkin, 1968; Harms, 1974; Hansbrough, 1968; Balmer, Owens, and Jorgenson, 1975). Russell noted a steady decline in survival of Virginia pine through 15 years of growth related to spacing and age. At five years, all spacings had 94% survival; at 10 years, trees at 4' by 4' and 6' by 6' had 84% survival while 93% of trees 8' by 8' were alive; at 15 years, the survival rates for the three spacings, from closest to widest, were 54%, 74% and 86% (Russell, 1979). Some workers with loblolly pine have reported no effect on survival by spacing at age 10 (Owens, 1974) and at age 17 (Campbell and Mann, 1974). At least one study of loblolly pine has shown highest survival on the narrowest spacing (6' by 6') (Box, Applequist, and Linnartz, 1965).

Adequate survival is especially important for stands with lower densities since the residual stands will be smaller at any given rate of mortality than those of stands planted at higher densities. The trend of higher survival at lower densities is borne out by the widely reported effect of higher merchantable volume at lower densities (Balmer, Owens, and Jorgenson, 1975; Hansbrough, 1968; Reukema, 1959; Russell, 1979). Red pine exhibited greater rates of increase in basal area and merchantable volume through age 25 in wider spacings than in narrower (Bramble, Cope, and Chisman, 1949). Lundgren (1981) found that although red pine produced maximum total volume at 1,500-1,600 trees per acre, merchantable cubic foot volume was maximized at 800 trees per acre and merchantable board foot volume was maximized at only 200 trees per acre. Greater volume at intermediate spacings may only be suitable for use as pulp; sawtimber production on short rotation is apparently limited to relatively wide spacings (Balmer, Owens, and Jorgenson 1975; Bassett, 1969; Russell, 1979).

Pruning And Tree Form

Another widely held opinion is that dense spacing encourages superior form. There is some support for this contention, mainly from earlier workers. Red pine showed good form when grown at 5' by 5' and 6' by 6', producing holes which were fragile, "narrow cylinders" as opposed to more tapered trees grown at 10' by 10' which were much less prone to ice damage (Bramble, Cope, and Chisman, 1949). Stevenson and Bartoo (1939) also found that red pine was better formed when grown at 5' by 5' and 6' by 6' than at wider spacings. Jack pine grown at 8' by 8' had "poor form" (Ralston, 1953). On the other hand, computer models have shown that initial spacing has only a small and temporary effect on form in red pine and is not significant over a full rotation. Also, differences in form among spacings had no influence on "economic analyses" (Lundgren, 1981). McClurkin (1976) reported that form class of loblolly pine was independent of spacing and Bassett (1967) even found that loblolly produced higher quality poles on lighter stockings.

Conventional arguments have indicated that early branch death, presumably because of low light intensity or heavy moisture competition (Toumey and Korstian, 1931), is promoted at dense spacings. Harms and Collins (1963) corroborated this view working with 12-year-old slash pine. Another slash pine study found significantly better pruning at spacing 8' by 8' and narrower than at any wider spacing (Bennett, 1969). Fourteen-year-old slash pine showed no differences in pruning among spacings, all trees retaining branches at small distances from the ground (Russell, 1958) and Bennett (1969) concluded that it was more economical to prune artificially trees planted at 15' by 15' than to plant at denser spacings when managing for sawtimber or veneer. Although 16-year-old red pine exhibited better pruning at 5' by 5' than at 10' by 10', average branch diameter was only 0.35 inches greater for the wider spacing (Stevenson and Bartoo, 1939). Projections by Lundgren (1981) confirmed this earlier report, showing less than 0.75 inches difference in average branch diameter at 16 feet on red pine between spacings of 21' by 21' and 7.5' by 7.5'. This study revealed that size and especially number of branches were more influenced by site index than stand density. Up to age 25 in red pine, there were no differences among spacings in pruning (Bramble, Cope and Chisman, 1949). Russell (1979), showed that density had no effect on pruning in 15-year-old Virginia pine, and Hopkins (1958) contended that pruning in loblolly pine was mainly a function of the amount of subdominant hardwoods in the stand.

Crown Size

One area of relatively widespread agreement amid the controversy over spacing effects is the behavior of crown size at differing stand densities. At spacings ranging from 4' by 4' to 16' by 16', slash pine shows consistent enlargement of crown as spacing widens (Bennett, McGee and Clutter, 1960; Russell, 1958; Ware and Stahelin, 1948). Loblolly pine has shown not only an increase in percent live crown as density decreased (Box, Applequist and Linnartz, 1965), but a crown diameter effect highly correlated with fluctuations in dbh as spacing varied (Owens, 1974). Russell (1979) found the usual increase in percent live crown in Virginia pine as spacing widened.

Specific Gravity

There has been much controversy regarding the influence of stand density on wood density. Possibly the idea that a strong positive correlation existed became current because slower diameter growth rates in closely spaced trees crowded late wood rings together, making the wood appear to have a higher proportion of the dense summerwood. Evidence supporting this view is scarce. Loblolly and shortleaf pine grown from 4' by 4' to 8' by 8' showed significant influence of spacing on specific gravity of wood in the last four rings of 15-year-old trees. Trees grown at 5' by 5' had the highest specific gravity. Contradicting the theory that slow growth encourages higher specific gravity, however, the same study demonstrated that vigorous dominant trees at all spacings had higher specific gravities than intermediate and suppressed trees (Hamilton and Matthews, 1965). Another loblolly study found no significant differences among spacings from 4' by 4' to 10' by 10' in specific gravity of 20-year-old trees, but did reveal that, after row thinnings, the same trees at 30 years had higher specific gravity when planted at 6' by 6' (Echols, 1959).

Most researchers have, nonetheless, found little to support the theory. Zobel, Ralston and Robards (1965) examined loblolly pine stands with basal areas of from 50 to 135 square feet per acre in age classes from 13-19 years to 33-50 years and found both specific gravity and percent summerwood independent of stand density. Bennett (1969) showed that all spacings of slash pine from 6' by 6' to 7.5' by 15' had achieved 0.33 rings per inch (Southern Pine Inspection Bureau then-current requirements for a "dense" rating) by age 13 and concluded that spacing was related to specific gravity. Larson (1957) asserted that slash pine stand density was unrelated to percent summerwood and that the species could be grown at least up to 10' by 10' without impairment of summerwood percent. The range of specific gravity in red pine grown at spacings from 2' by 2' to 10' by 10' was only 0.01 (0.318 to 0.328) with the closest spacing having the lowest specific gravity (Baker, 1969). Thirty-year-old red pine produced six rings per inch even at a spacing of 15' by 15' (Lundgren, (1981).

Eastern White Pine

The question of spacing in white pine plantations is somewhat distinct from that of the southern yellow pines. There is far less emphasis in the literature on growth rates, though that is, to be sure, important, and far more emphasis on pruning, artificial and natural. This is readily explained by the virtual lack of a pulp market for white pine and the consequent concern for production of clear, high-quality sawtimber.

White pine exhibits intermediate tolerance to shading. Paul (1938) states that the tolerance of a species regulates how quickly its lower branches die but has no relation to the length of time these branches remain on the stem, as was confirmed by Funk, (1961), and Lane (1959). White pine in the Yale Forest was observed with dead branches on the stems nearly to the ground 60 to 80 years after branch death (Hawley and Clapp, 1942). Arnold and Rolfe (1978) comment that the species will not begin natural pruning until 90 years. Paul (1938) studied 52 to 58 year-old stands of white pine spaced at 405 and 1,058 trees per acre. He found branches on the lower 20 feet of the bole remained alive, on the average, for 15 years. The dead stubs persisted on the trunk for an average of 27 more years. Thus on a 50 year rotation, only the last seven years of growth would produce clear lumber; one-third of rotation would be spent producing wood with tight knots, and over half the rotation would be devoted to growing wood encasing the even more detrimental loose knots.

It is clear that, left to itself, white pine will be knotty no matter what its initial spacing may be. However, it is possible to regulate the degree of knottiness. Branch diameter is smaller on close spacings than on the wide (Wilson, 1959). Paul (1938) found that 72.5% of knots on trees grown at 1,058 trees per acre and 64.3% of knots on trees grown at 450 trees per acre were smaller than one-half inch in diameter. However, he concluded,

> Overcrowding sufficient to retard branch development in dense stands also decreases volumetric increment of individual trees. In a short rotation this serious disadvantage more than offsets the slight benefits gained by close stocking.

While knot size may be affected by stand density, the number of knots apparently is not. In the same study quoted above, the author found no relation between stand conditions and knot numbers (Paul, 1938). Lane (1959) observed that knot numbers varied with site quality.

Knot characteristics can be manipulated by affecting growth rate. Since white pine is uninodal, a longer internode will produce a tree with fewer knots per linear foot of height (Paul, 1938). Unfortunately, spacing has a limited effect on height growth, wider spacing producing only slightly taller trees in other coniferous species. Studies have demonstrated no effect on white pine height growth or internode length (Hunt and Mader, 1970; Wilson, 1959). Diameter growth, more amenable to control by stand density, also can affect knot characteristics. Paul (1938) states that rapid early diameter growth will cause a greater proportion of a branch to be engulfed in the bole while still alive, thus reducing the amount of loose knot volume. White pine clearly exhibits increased diameter growth as growing space increases (Wilson, 1959; Hunt and Mader, 1970).

Most authors agree on the futility of trying to produce clear lumber on untreated white pine over a reasonable length of time. Therefore, much attention has been given to artificial pruning. Lane (1959) flatly states that good knot characteristics can be produced only by artificial pruning. Funk (1961) gives seven reasons to prune white pine. Pruning improves quality; improves form; provides easier peeling; reduces transmission of rot from dead branches to bole; reduces the risk of crown fires; reduces fuel after harvest; returns nutrients to the ground at a steady rate; and provides better working conditions in the stand. Ultimately, the decision to prune is economic. The labor and capital costs of pruning must be balanced against the value added by the operation. Pruning has generally been shown to be as lucrative as any other silvicultural operation (Smith, 1962).

CHAPTER II

METHODS

The Study Site

The 32-acre species-spacing study is located on The University of Tennessee Highland Rim Forestry Experiment Station near Tullahoma, Tennessee. The soil is Dickson silt loam underlain by a fragipan at a depth of about 24 inches. Topography is generally flat with some mild relief.

The previous forest cover was commercially clearcut and cull trees were injected with 2,4-D. The area was mist-blown with 2,4,5-T to kill brush and herbaceous material. Burning completed planting preparation. In early spring, 1966, 1-0 seedlings of loblolly, shortleaf and Virginia pine, and 2-0 seedlings of white pine were planted using the bar method.

The experiment was laid out in a split-plot design comparing four species (loblolly, Virginia, shortleaf, and eastern white pine) in the main plots and four spacings (6' by 6', 9' by 9', 12' by 12' and 15' by 15') in the split plots. Experimental units or plots consist of a single species planted in four spacings in a one-half acre square. The experiment is replicated four times for a total area of 32 acres in 64 plots.

Previous Measurements

After five years, all trees were measured for height and survival. After 10 years, the experiment was measured again (Thor, Rennie, and Omiyale, 1976). One-hundred percent of trees planted at 15' by 15', 50% of trees planted at 12' by 12', 33% of trees planted at 9' by 9' and 16.6% of trees planted at 6' by 6' were measured. Selection of the sample was done systematically, by rows. Total height, diameter at breast height (dbh), height to live crown, and survival were observed.

The Present Study

The data which are the basis of the current analysis were taken at the end of the sixteenth growing season in September, 1981. Survival, total height, height to the first live branch, distance from the ground to the first remaining branch, crown radius and dbh were recorded. White pine was measured for the number of branches in the whorl nearest breast height and the diameter of the largest branch in that whorl. (See Table 1).

Border Effect

In a preliminary survey, the plots were mapped on grids to determine the number of positions in each. Remnants of the hardwood stand were observed to have persisted. These isolated overstory trees were mapped on the grids.

A definition of border effect was necessary before measurement began. Border effect is an external influence on a pine resulting from (a) the position of a pine in an exterior row, (b) the position of a pine in an interior border row, or (c) the position of a pine adjacent to an overstory hardwood.

TABLE 1

Units and Abbreviations

Characteristic	Unit	Abbreviation
Total Height	Meters	M
Diameter at Breast Height	Centimeters	CM
Basal Area per Tree	Square Meters	M^2
Height to first Live Branch	Meters	m
Height to First Remaining Branch	Meters	M
Percent Live Crown	Percent	%
Volume per Tree	Cubic Meters	M^3
Basal Area per Hectare	Square Meters per Hectare	M^2/ha.
Volume per Hectare	Cubic Meters per Hectare	M^3/ha.
Percent Survival	Percent	%

Sampling For Survival

It was assumed that border effects do not affect survival. A sample size of 70 positions per plot was estimated to yield a maximum confidence interval of ±5.8% and this interval was considered acceptable. Every position on each plot was numbered and a computer-generated random arrangement of these numbers was obtained. The first 70 numbers on these lists were measured for that parameter.

Sampling For Quantitative Characteristics

It was determined that a sample size of 35 trees per plot would yield a confidence interval of ±0.5 meters (m) for total height and ±1.3 centimeters (cm) for dbh and that these intervals were acceptable errors. Calculations were based on variances for total height and dbh obtained for the 10-year data.

Position of pines in plot borders was assumed to affect quantitative characteristics. To this end all border row trees were excluded from the sample. An exterior border row was defined as a row of trees which formed the edge of the study. An interior border row was defined as a row of trees of one unit which bordered another unit; however, if the two units were of the same species and of spacings did not differ by more than one spacing class (for instance, 6' by 6' and 9' by 9' plots of white pine), then the trees in the interior border rows between them were eligible for inclusion in the sample.

A zone of border effect was established around each overstory hardwood. It was assumed that a pine could not grow to dominance within the zone of border effect of a hardwood. Hardwoods in plots of each species were selected and the distance from them to the nearest dominant pine in four directions was measured. The average distance of seven meters was assumed to be the effect around every hardwood which interfered with the sampling process. Trees inside that circle were excluded from the sample.

After all exclusions, a residual stand remained on each plot from which 35 trees were chosen at random for measurement. In one case, the residual stand did not contain 35 trees. All nonborder trees were measured on this plot.

One plot of Virginia pine planted at 6' by 6' contained numerous loblolly pine, apparently incorrectly planted as Virginia pine. It was excluded from the study. Another plot of Virginia pine planted at 9' by 9' also contained loblolly but enough rows of pure Virginia pine were available that a sufficient sample could be drawn uninfluenced by the other species.

Four plots of shortleaf pine, two planted at 12' by 12' and two at 15' by 15', had suffered extremely heavy mortality. All trees were measured on these plots.

Sixteen Year Measurement Definitions

In all, seven parameters were measured. Total height was measured with a Haga altimeter to the nearest 0.5 m; dbh was measured at 1.3 m from the ground with calipers to the nearest centimeter; height to live crown, defined as the distance from the ground to the first living branch, was measured with the Haga to the nearest 0.5 m; height to the first remaining branch, the distance from the ground to the first clearly visible limb or remnant thereof, was determined with a cloth tape to the nearest 0.5 m; and crown radius, the distance from the bole to the drip line, was determined in the four cardinal directions with cloth tape to the nearest 0.5 m and the four values averaged. Two measurements were performed on white pine only. The number of branches in the whorl nearest breast height was counted and the diameter of the largest branch in that whorl was taken with the calipers to the nearest cm.

Statistical Analysis

Statistical analyses were performed on the 16 year data using the Statistical Analysis System (SAS), a commercial software package available at The University of Tennessee, Knoxville. Five new variables were calculated from the data. Basal area per tree was calculated from the formula $0.00007854(DBH)^2$. Basal area per hectare (ha) was obtained through expansion. Percent live crown was calculated as (Total Height-Height to live crown)/(Total Height) 100.

Identifying an appropriate formula for tree volume was difficult. At 16 years, the trees of all species were segregating into general diameter-class groupings. Some fast growing individuals were approaching small sawtimber size, greater than 28 cm dbh; a large number of trees fell into diameter classes between 12.7 and 28 cm; and about 15% were smaller than 12.7 cm dbh. Furthermore, the fact that the four species were to be considered together raised the question of comparability of volume formulas generated from different sources. Very few volume tables extend over such a wide range of diameter. At the extremes of the tables, figures diverge more and more actual values. Smalley and Bower's (1968) work in shortleaf and loblolly pine and Vimmerstedt's (1961) work with white pine provided volume tables which came closest to fitting this data. Unfortunately, none extended over the full range of diameters measured and there was no suitable table for Virginia pine. The problem of comparability among the formulas persisted. Use of the formula for the volume of a cone was briefly considered, but it was deemed desirable in an applied situation such as this that more useful and practical figures be produced. Regression coefficients (b_1) among the formulas under consideration differed in a range across all species of only 0.04. Therefore, a compromise figure among these coefficients was calculated. The volume formula for all species became $0.002675(DBH)^2(\text{Total Height})$ where dbh and total height are in inches and feet, respectively, and volume was in cubic feet. This was then multiplied by 0.028317 to convert dbh to centimeters, total height to meters and volume to cubic meters. Volume per hectare was calculated by simple expansion.

Each parameter was first analyzed in the multiple regression procedure of SAS in the split-plot design (hereinafter called "combined analysis") of the general form

$$Y = b_0 + b_1(\text{Species}) + b_2(\text{Blocks}) + b_3(\text{Species X Blocks}) + b_4(\text{Spacings}) + b_5(\text{Spacings x Species}) + \text{Error}$$

Residual values of the analysis were calculated and plotted and all data were found to be normally distributed. Duncan's Multiple Range tests were performed by species and spacings for those variables not showing a significant (α=0.05) species by spacings interaction. These variables were volume per hectare, basal area per hectare and survival.

All other variables were found to have significant interactions and were analyzed separately by species in a randomized complete block design (hereinafter called "separate analysis") of the general form

$$Y= b_0 + b_1(\text{Spacings}) + b_2(\text{Blocks}) + \text{Error}$$

Duncan's Multiple range tests were performed for all variables by spacing.

Survival data, due to its binomial nature, was first collected on a per plot basis as a decimal figure, calculated as the number of live trees divided by the per plot sample size. These figures were transformed with the arcsine of the square root, $\text{Arcsin}\sqrt{Y_i}$, then analyzed using SAS.

Conclusions drawn from comparisons among the 5-, 10- and 16-year data should be viewed with some caution. The results were not statistically compared. Comparisons were based on a simple examination of graphs and tables of mean values and, in some cases, of calculations of differences among means. Differing sampling methods and associated probabilities were employed in each case. When comparing volume figures of the 10- and 16-year data, the reader should bear in mind that very different formulas were used to calculate the values.

CHAPTER III

RESULTS

Introduction

The table of significant effects (See Table A-1, Appendix) summarizes the results of analysis of variance for each variable, using the split-plot design. Almost every variable showed a significant species by spacing interaction, indicating differential behavior of the four species as spacing changed. Since, as detailed in Chapter II, these parameters required separate analysis, these results are given by species. Results from the combined analysis of variables which did not show the significant interaction are given separately. All values, unless otherwise stated, are means.

Loblolly Pine

Total Height

Both blocks and spacings showed significant differences (See Table A-2, Appendix). There was little change in height as spacing widened (See Table A-3, Appendix). The range in height by spacing was only 0.62 m (12.33 m to 12.95 m) from 15' by 15' to 9' by 9'. The two intermediate spacings produced the tallest trees. Duncan's Multiple Range tests showed the extremes of the range to be significantly different.

Comparison of values for total height at 16 years with those from earlier measurements showed little change in relative heights among spacings (See Figure 1, Appendix). Absolute differences among spacings were small at all measured ages. The amount of added height in the last six years (about 5 to 6 m) is approximately the same as for the previous five years (4 to 5 m).

DBH

Both blocks and spacing showed significant differences in diameter. (See Table A-2, Appendix). There is a strong trend to larger dbh as spacing widens. DBH for each spacing is significantly different from every other. The range in values is 7.19 cm (16.04 to 23.23 cm) (See Table A-3, Appendix).

This trend can be detected in the 10 year data but has become much more pronounced in the intervening six years (See Figure 2, Appendix). Not only has absolute dbh increased by spacing but growth rate increases as spacing widens. The dbh at 15' by 15' increased by almost 10 cm while at 6' by 6' it increased approximately 5 cm over the last six years.

Basal Area Per Tree

Analysis revealed significant differences among blocks and spacings (See Table A-2, Appendix). Basal area per tree showed the same response as dbh to wider spacings. Spacings ranked from narrowest to widest in order of the value of basal area per tree. The range was 0.03 m^2 (See Table A-3, Appendix).

This trend was evident at 10 years and has strengthened considerably since then (See Figure A-3, Appendix). Growth rates increase with wider spacings. Increases in basal area range from 0.03 m^2 for trees at 15' by 15' to 0.01 m^2 for trees at 6' by 6'.

Height To First Live Branch

Blocks and spacings showed significant differences in height to first live branch (See Table A-2, Appendix). There is a strong trend to lower live crowns as spacing widens. The range is 3.56 m (3.81 m to 7.37 m) from 15' by 15' to 6' by 6' (See Table A-3, Appendix). Mean values for each spacing are significantly different from all others ranking in order from 6' by 6' to 15' by 15' .

The differences between the narrower spacings and the wider spacings have become more pronounced in the last six years (See Figure A-4, Appendix). At 10 years there was a steady drop in height to first live branch from 6' by 6' to 15' by 15', while at 16 years values for trees planted at the two narrow spacings have come closer together as a result of a slowing of the rate of crown retreat in trees planted at 6' by 6'. The rate of crown retreat is most rapid among trees planted at 9' by 9', followed by those planted at 12' by 12'.

Percent Live Crown

Significant differences in percent live crown were found among blocks and spacings (See Table A-2, Appendix). As might be inferred from the results of height to first live branch, percent live crown shows a strong tendency to increase with wider spacing (See Table A-3, Appendix). The mean for each spacing is significantly different from every other. Mean values range, in order from 6' by 6' to 15' by 15', from 41.0% to 68.5%, a difference of 27.4%.

Height To First Remaining Branch

No significant differences were detected among spacings but were found among blocks (See Table A-2, Appendix). The range of values was 0.16 m (1.49 m to 1.65 m).

Crown Radius

Both blocks and spacings had significant differences (See Table A-2, Appendix). Crown radius of each spacing differed significantly from every other (See Table A-3, Appendix). Crown radius increased with each wider spacing from 1.20 m for trees planted at 6' by 6' to 2.77 m for those planted at 15' by 15', for a total range among means of 1.57 m.

Volume Per Tree

Both blocks and spacings were shown to have significant differences (See Table A-2, Appendix). Like basal are per tree volume per tree showed a strong response to widening spacing. The wider the spacing, the greater the volume per tree (See Table A-3, Appendix). Each value was shown to be significantly different from the other. Volume ranged from 0.14 m^3 among trees planted at 6' by 6' to 0.28 m^3 for trees at 15' by 15'.

Comparison of 16 year and 10 year data showed a large jump in volume production per tree with increases ranging from 0.23 m^3 for trees at 6' by 6' to 0.50 m^3 for trees at 15' by 15' (See Figure A-5, Appendix). It was apparent that growth rates increased as spacing widened.

Shortleaf Pine

Due to very heavy mortality at spacings 12' by 12' and 15' by 15' on blocks one and two among the shortleaf pine, means were calculated for those spacings both with and without information from the four "problem plots." Where the values obtained were sufficiently different to merit note, both are reported.

Total Height

Both blocks and spacings had significant differences in total height (See Table A-4, Appendix). There is a significant decline in height as spacing widens. The range in total height is 1.34 m, from 10.38 m among trees planted at 6' by 6' to 9.04 m among trees planted at 15' by 15' (See Table A-5, Appendix). Mean separation shows values for trees planted at 6' by 6' and 9' by 9' not to be significantly different from all other values. The decline in height from trees at 6' by 6' to trees at 15' by 15' is less steep if problem plot data are eliminated. In that case, the range is only 1.09 m.

In earlier measurements there was little difference among spacings in total height (See Figure A-1, Appendix). No overall trend was discernable. The trees have added from 4 to 5 m of height in the last six years, trees planted at 6' by 6' growing fastest.

DBH

There were significant differences among spacings and blocks in dbh (See Table A-4, Appendix). DBH showed a tendency to aggregate into two groups, the narrow spacings and the wide (See Table A-5, Appendix).

Within these groups, dbh did not vary significantly; between them, it did. There was a large jump in dbh from trees at 9' by 9' to trees at 15' by 15', from 13.83 cm to 16.08 cm. The range of values was 3.05 cm from 13.51 cm for trees at 6' by 6' to 16.56 cm for trees at 12' by 12'. If problem plot data are ignored, the mean dbh of trees at 15' by 15' plots becomes the largest at 16.63 cm.

Tree diameters have increased by 7.00 to 8.50 cm in the last six years, with the trees on the wider spacings growing more than those on the narrower spacings (See Figure A-2, Appendix). The trend toward grouping the spacings is just beginning at 10 years. It is quite pronounced by 16 years.

Basal Area Per Tree

There were significant differences among blocks and spacings in basal area per tree (See Table A-4, Appendix). A positive response to widening spacing was observed, with the same tendency to aggregation by spacing width groups as in dbh (See Table A-5, Appendix). If problem plots are eliminated, the range was extended but the trend was still the same.

At 10 years, this trend to aggregation was very slight but observable (See Figure A-3, Appendix). Basal areas had increased by 0.01 to 0.02 m^2, with greater growth occurring in the wider spacings.

Height To First Live Branch

There were significant differences among blocks and spacings in height to first live branch (See Table A-4, Appendix). The two widest spacings did not show significant differences (See Table A-5, Appendix).

Exclusion of problem plot data did not materially affect results. The range was 2.07 m, from 3.29 m for trees at 15' by 15' to 5.36 m for trees at 6' by 6'.

Comparison of 10 and 16 year data showed an increasingly rapid retreat of the live crown on trees planted at narrow spacings (See Figure A-4, Appendix). Distance from the first live branch to the ground had increased by from about 1.5 to 3.0 m.

Percent Live Crown

Significant differences among blocks and among spacings were found in percent live crown (See Table A-4, Appendix). As indicated by the results from total height and height to the first live branch, percent live crown shows a marked increase as spacing widened (See Table A-5, Appendix). Percent live crown for trees at 15' by 15' and 12' by 12' were not significantly different, but values for the other spacings were significantly different from all others. Values ranged from 48.1% for trees at 6' by 6' to 64.3% for trees at 12' by 12', for a total range of 16.2%.

Height To First Remaining Branch

Analysis showed significant differences in height to the first remaining branch among blocks but not among spacings (See Table A-4, Appendix). The range among means for spacings was 0.11 m.

Crown Radius

Both blocks and spacings showed significant differences in crown radius (See Table A-4, Appendix). The effect of spacing on crown radius mirrored that of dbh (See Table A-5, Appendix). There was a strong tendency to increase crown width as spacing widened and the values separated into significantly distinct groups of wide and narrow spacings. The range of values was 0.59 m, from 1.19 m for trees planted at 6' by 6' to 1.78 m for trees planted at 15' by 15'. Differences became more pronounced if problem plot data was eliminated.

Volume Per Tree

Both blocks and spacings showed significant differences in volume per tree (See Table A-4, Appendix). The trend across spacings in volume per tree was very close to that in basal area per tree, particularly when the problem data were removed (See Table A-5, Appendix). Volumes for the two narrow spacings were not significantly different, and there was a large increase in volume from 9' by 9' to 12' by 12'. After the peak at 12' by 12', a slight decline occurred between 12' by 12' and 15' by 15' spacings. These two values were significantly different if problem data were included. The decline was much less steep if such data were ignored. The range was 0.02 m^3 from the value for trees at 6' by 6' to the mean for trees at 12' by 12' 0.079 m^3 to 0.112 m^3.

No trend was discernable in the 10 year results (See Figure A-5, Appendix). Growth has been fastest in trees spaced at 12' by 12', slowest in those spaced 9' by 9'.

Virginia Pine

Total Height

There were significant differences among both blocks and spacings in total height (See Table A-6, Appendix). There was a trend in Virginia pine for trees to be shorter as spacing widened (See Table A-7, Appendix). Total height of trees planted at 12' by 12' and 15' by 15' were not significantly different, but the means for the other two spacings were significantly different from all others. Trees planted at 6' by 6' were the tallest. The range in means was 2.01 m, from 9.49 m for trees at 12' by 12' to 10.5 m for trees at 6' by 6'.

Height growth ranged from less than 4 m to more than 5 m over the past six years, with the greatest growth occurring in trees planted at narrow spacings (See Figure A-1, Appendix). The trend toward taller trees in narrower spacings was evident from earlier results.

DBH

Significant differences appeared among spacings but not among blocks in dbh (See Table A-6, Appendix). DBH increased as spacing widened (See Table A-7, Appendix). DBH for each spacing were significantly different from every other one and were larger in order from the narrowest spacing to the widest. There was a slight tendency for values to aggregate into narrow-spacing/wide-spacing groups. The range was 5.57 cm, from 13.04 cm for trees at 6' by 6' to 18.61 cm for trees planted at 15' by 15'.

This trend has become more pronounced in the last six years, indicating that growth rates were more rapid at wider spacings (See Figure A-2, Appendix). Mean growth by spacings has ranged from approximately from 4.5 to 6 cm in the last six years.

Basal Area Per Tree

There were significant differences among spacings but not among blocks (See Table A-6, Appendix). The trend in data mirrored that for dbh (See Table A-7, Appendix). The range was 0.01 m^2 from means of 0.04 m^2 for trees at 6' by 6' to 0.03 m^2 for trees at 15' by 15'.

The trends described above have intensified in the last six years (See Figure A-3, Appendix). Growth ranged from 0.01 m^2 for trees at 6' by 6' to 0.03 m^2 at 15' by 15'.

Height To First Live Branch

There were significant differences among spacing but not among blocks in values for height to first live branch (See Table A-6, Appendix). There was a strong drop in values as spacing widened from 9' by 9' to 12' by 12'. Height to first live branch tended to aggregate into narrow/wide spacing groups although each value was significantly different from every other. The mean values ranged from 1.77 m for trees at 15' by 15' to 6.57 m for trees at 6' by 6'.

This trend was evident at 10 years but had become much more pronounced, with rapid retreat of live crowns at narrow spacings (See Figure A-4, Appendix). Retreats have averaged from 1 to 5 m in the last six years.

Percent Live Crown

Spacings and blocks showed significant differences in percent live crown (See Table A-6, Appendix). There was a strong increase in percent live crown as spacing widened, from 42.4 for trees at 6' by 6' to 81.2% for trees at 15' by 15'. All values were significantly different from all others. A large increase was evident between the values for trees at 9' by 9' and 12' by 12' and the means tended to aggregate slightly, values for trees at 6' by 6' with those for 9' by 9' and values for trees at 12' by 12' with those at 15' by 15' (See Table A-7, Appendix).

Height To First Remaining Branch

There were significant differences among both blocks and spacings in height to first remaining branch (See Table A-6, Appendix). Height to first remaining branch for trees planted at 12' by 12' and 6' by 6' and for trees planted at 6' by 6' and 9' by 9' were not significantly different (See Table A-7, Appendix). Height to the first remaining branch was significantly lower among trees planted at 15' by 15' than at any other spacing. Mean values ranged from 0.44 m for trees at 15' by 15' to 0.66 m for trees at 12' by 12'.

Crown Radius

Both blocks and spacings showed significant differences in crown radius (See Table A-6, Appendix). A definite trend to wider crowns as spacing increased was evident in these results. Each crown radius was significantly different from every other, ranging from 1.12 m for trees at 6' by 6' to 2.75 m for trees at 15' by 15' (a total range of 1.63 m).

Again, it was seen that mean values for wider spacings were close and those for narrow spacings were close, with a definite break between values for trees at 9' by 9' and those at 12' by 12' (See Table A-7, Appendix).

Volume Per Tree

There was a significant space effect but no significant block effect on volume per tree (See Table A-6, Appendix). Volume per tree generally increased as spacing widened (See Table A-7, Appendix). Trees volume at 6' by 6' was significantly smaller than at other spacings. Values for trees at 9' by 9' and 12' by 12' were not significantly different from each other and the mean value for trees at 15' by 15' was significantly larger than any other value. Mean values ranged from 0.08 m^3 for trees at 6' by 6' to 0.136 m^3 for trees at 15' by 15', with a large jump from the mean of trees at 6' by 6' to that of trees at 9' by 9'.

Growth in the last six years has ranged from about 0.01 m^3 to 0.06 m^3, with more growth occurring in the trees at the wider spacings (See Figure A-5, Appendix). The trend of extremes diverging from the middle was slightly apparent at age 10.

Eastern White Pine

Total Height

Both spacings and blocks showed significant differences in total height (See Table A-8, Appendix). White pine showed a slight but definite trend to increasing height as spacing widened (See Table A-9, Appendix). Height at the wider two spacings and of the narrower two spacings did not differ significantly within those groupings but did differ between them. The total range among means was 0.79 m from 10.96 m for trees at 6' by 6' to 11.75 m for trees at 15' by 15'.

This trend has emerged since 10 year data were collected. Growth has been greater in the wider spacing (See Figure A-1, Appendix). Growth has ranged approximately 5 to 6 m in the last six years.

DBH

Only spacings showed significant differences in dbh (See Table A-8, Appendix). There was a very strong trend to increasing dbh as spacing widened (See Table A-9, Appendix). Each value was significantly different from every other by spacings. The range of means was 6.82 cm, from 14.04 cm for trees at 6' by 6' to 20.86 cm for trees at 15' by 15'.

The advantage in dbh that trees planted at the wider spacings enjoyed has intensified in the last six years (See Figure A-2, Appendix). Growth in mean values ranged from seven to 12 cm, approximately, with wider spacings exhibiting the greater growth.

Basal Area Per Tree

There were significant differences among spacings but not among blocks in basal area per tree (See Table A-8, Appendix). Like dbh, mean basal area per tree increases strongly as spacing widened (See Table A-9, Appendix). The range of mean values was 0.02 m^2, from 0.02 m^2 for trees at 6' by 6' to 0.04 m^2 for trees at 15' by 15'.

Separation of means in the widest three spacings occurred most rapidly in the wider spacings only in the last six years (See A-3, Appendix). Growth in the last six years ranged from about 0.01 m^2 to 0.03 m^2.

Height To First Live Branch

There were significant differences among both spacings and blocks (See Table A-8, Appendix). The distance from the ground to the first live branch decreased sharply as spacing widened. Mean separation showed means by spacings to be each significantly different from all others. The range was 3.51 m from 2.47 m for trees at 6' by 6' to 5.98 m for trees at 15' by 15' (See Table A-9, Appendix).

Crowns at the two narrow spacings have retreated relatively rapidly over the last six years while those on trees planted at the wider spacings have done so more slowly (See Figure A-4, Appendix). Mean values for trees at 6' by 6' and 9' by 9' spacings were fairly close (0.71 m difference) and a sharp decline occurred from values for trees at 9' by 9' to those for trees at 12' by 12', with an even more abrupt decline to the widest spacing. Retreat of crown ranges approximately from 2 to 5 m over the past six years.

Percent Live Crown

There were significant differences among both spacings and blocks (See Table A-8, Appendix). Percent live crown increased rapidly as spacing widened, from 44.9% for trees at 6' by 6' to 79% for trees at 15' by 15'. All figures differed significantly from all others. The means for trees planted at the two narrow spacings were relatively close while large gaps separated the other values from each other and from the narrow spacing group (See Table A-9, Appendix).

Height To First Remaining Branch

Height to first remaining branch showed significant differences among spacings and blocks (See Table A-8, Appendix). Duncan's Multiple Range tests detailed differences among spacings, but no clear pattern was discernable (See Table A-9, Appendix). The range of values was 0.08 m, from 0.05 m for trees at 9' by 9' to 0.13 m for trees at 6' by 6'.

Crown Radius

Significant differences among blocks and spacings were found in crown radius (See Table A-8, Appendix). Crown radius increased as spacing widened. Each value was significantly different from every other by spacing (See Table A-9, Appendix). The range was 1.24 m from 1.19 m for trees at 6' by 6' to 2.43 m for trees at 15' by 15'.

Volume Per Tree

Significant differences were found among spacings but not among blocks in volume per tree (See Table A-8, Appendix). Volume per tree rose rapidly as spacings widened, from 0.098 m^3 at 6' by 6' to 0.218 m^3 for trees planted at 15' by 15' (See Table A-9, Appendix). Each spacing is significantly different from all others.

This trend has strengthened and become more consistent in the last six years (See Figure A-5, Appendix). Growth has been greatest in the wider spacings. Growth has ranged from 0.09 m^3 to 0.21 m^3. Trees planted at 12' by 12', trailing in volume production those trees planted at 9' by 9' at age 10, have now out-produced those trees by 0.04 m^3 per tree in the last six years.

Branch Number

There were significant differences among blocks but not among spacings (See Table A-8, Appendix). There was no trend in the number of branches in the whorl nearest breast height by spacings.

Branch Diameter

Significant differences appeared among spacings and blocks in branch diameter (See Table A-8, Appendix). There was a trend for branch diameter to increase as spacing widened (See Table A-9, Appendix). Mean separation showed values of the narrowest spacing and widest spacing to be significantly different from all others while diameters of the two middle spacings were not significantly different from each other, aggregating in a middle group. The means ranged from 1.94 cm for trees at 6' by 6' to 2.69 cm for trees at 15' by 15', a difference of 0.75 cm (See Table A-9, Appendix).

Variables Not Showing Significant Interaction

Basal Area Per Hectare

Analysis of variance showed basal area per hectare to be significantly influenced by species and spacing but not by blocks or species-spacing interaction (See Table A-10, Appendix). As spacing widened, there was a strong tendency for basal area per hectare to decline (See Table A-11, Appendix). Mean separation showed values by spacings each to be significantly different from all others, ranging from 11.47 m^2/ha for trees at 6' by 6' to 36.59 m^2/ha for trees at 15' by 15', a range of 25.12 m^2/ha. There was a sharp drop in volume from trees planted at 6' by 6' to trees planted at 9' by 9' and successively less steep drops to wider spacings.

There was somewhat less variation among species. Mean values for loblolly and white pine were not significantly different from each other (See Table A-12, Appendix). Shortleaf and Virginia pine were significantly different from all others. The means ranged across species by 14.92 m^2/ha, from 13.48 m^2/ha for shortleaf pine to 28.4 m^2/ha for loblolly pine. Loblolly pine and white pine showed greater basal area growth per hectare than did either Virginia or shortleaf pine.

Over the last six years, white pine has exhibited the greatest growth in basal area per hectare, periodic growth ranging from about 13 to 28 m^2/ha (See Figure A-6, Appendix). Growth in all species has been greatest at narrower spacings with trees planted at 6' by 6' increasing their lead more rapidly as time goes on.

Volume Per Hectare

There were significant differences among species and spacings but not among blocks or species-spacing interaction in volume per hectare (See Table A-10, Appendix). The results of analysis of volume per hectare are essentially identical to those of basal area per hectare. As spacings change, means based on all four species differ significantly from one another and volume per hectare increased steadily as spacing narrowed (See Table A-13, Appendix). From a low of 65.27 m^3/ha among trees planted at 15' by 15' to a high of 214.79 m^3/ha in trees planted at 6' by 6', mean values ranged 149.52 m^3/ha.

Again, loblolly and white pine are the largest volume producers, but this time are significantly different, as were all species from every other. The range of volume was 113.41 m^3/ha from 69.44 m^3/ha in shortleaf pine to 182.85 m^3/ha in loblolly pine (See Table A-14, Appendix). There was a distinct gap between volumes at all spacings of loblolly and white pine as a group, and Virginia and shortleaf pine, as a group.

Survival

The only significant effect on survival was species (See Table A-10, Appendix). Spacing, blocks and species-spacing interaction showed no significant differences. Loblolly and Virginia pine showed survival rates in the range of 70% to 80%; 85% of white pines survived to age 16 (See Table A-15, Appendix). Due to heavy mortality in four problem plots, mean survival for shortleaf pine was only 55%. If those plots were ignored, the mean rose to around 71%, not significantly different from Virginia pine at 72.4%.

Survival rates have dropped steadily over time over all spacings and in all species (See Figure A-7, Appendix). Mortality has occurred most slowly in white pine, with drops in survival rates running at around 10% since the five year data were collected. The yellow pines all have lost between 10% and 20% of original totals to mortality in the last 11 years.

Correlated Variables

Correlation coefficients were generated for all variables (where possible) on an overall and species by species basis (See Table A-16, Appendix). Only a few variables were highly correlated. DBH was highly correlated with crown radius ($r = 0.75$). Total height and dbh showed an r value of 0.56. Total height and volume per tree were associated with an r of 0.67. Volume per tree correlated very highly with basal area per tree ($r = 0.97$), and percent live crown and height to live crown were strongly negatively correlated at $r = -0.87$. Volume per hectare and basal area per hectare were very highly associated, with $r = 0.99$. Separately, the pattern of correlated variables was very much the same.

CHAPTER IV

DISCUSSION

Species Comparison

The characteristics most indicative of overall vigor and growth are total height and dbh. On these two variables depend the values generated for basal area and volume, characteristics most often examined when some idea of the total growth of the tree is desired. Using these traits as a yardstick, loblolly pine emerges as the most vigorous by far of the species studied. It produces, on the average, larger trees at every spacing than any of the other pines in the study. Consequently, basal area and volume per tree are greater than those for any other species.

The next most vigorous producer of wood is white pine. It is distinctly second to loblolly pine but is a distinctly more rapid grower than Virginia or shortleaf pine. Its greater growth becomes most apparent when mean values of basal area and volume are compared. When per hectare figures for these characteristics are calculated, white pine because of its better survival rates rivals loblolly pine. There is a substantial gap between loblolly and white pine, the fast growers, and Virginia and shortleaf pine, the slower growers. Particularly in total height, basal area and volume, the difference between the two pairs are relatively large compared to the differences among them. Generally, across all spacings, Virginia pine outgrows shortleaf pine. It produced larger trees and, consequently, trees with greater basal area and volume. In a ranking of overall vigor of growth, loblolly pine is clearly first, followed by white pine, and then by Virginia and shortleaf pine.

Total Height

Analyses showed statistically significant effects of spacing on the total height of trees. The range of mean values across spacings were about 1 to 2 m, enough to produce significant differences. A comparison of mean values across spacing of the four species shows an interesting divergence of behavior between white pine and the yellow pines. The yellow pines showed a steady decline in total height as spacing widened (loblolly pine peaks in height at 9' by 9' and declines thereafter); white pine increased in height as spacing widened. These trends have become apparent only in the last six years, although a slight decline in heights as spacing widened was discernable in Virginia pine at age 10.

Shorter trees are probably produced on the wider spacings due to different distribution of photosynthate from the narrow spacings. At the wide spacings, the greater amount of light causes the tree to produce a much wider crown and a larger bole. More carbohydrates are devoted to branch and stem growth than to height growth. A difference in height at age 16 of 2 m could translate into an understatement or overstatement of site index of up to 56 m. This mistake could cause a large error in volume prediction, certainly a significant difference to the practical resource manager.

A significant effect of spacing on the height of trees casts doubt on the concept of site index. Conventional theories of site index hold that such an influence should have no effect on the height of trees; otherwise the concept would be of little value. Several other studies have noted the influence of spacing on height. Further study is indicated (Balmer, Owens, and Jorgenson, 1975; Bennett, 1974; Collins, 1967; Hansbrough, 1968; and Shepard, 1974).

Other Variables

Analyses showed significant differences in height to first remaining branch among spacings and species, but no clear trends were discernable. It was expected from a review of literature that the height to the first remaining branch would decrease as apacing widened due to earlier limb death in trees planted closer together. This effect was not observed. Spacing unfortunately seems to have little effect on pruning, at least to age 16. This is contrary to expectations and no explanation is immediately apparent.

Any field study of spacing effects on tree growth will include the impact of mortality. As the stand ages, the death of individuals will naturally change the spacing around other individuals. It is not the purpose of this project to measure the effect of an ideal, constant space regimen, but rather to observe effects as they would occur in a commercial or private plantation.

Differences among the species are more pronounced. Loblolly pine prunes best, averaging about 1.6 m from the ground to the first remaining branch; shortleaf is next, with an average around 1.2 m; Virginia pine retains branches considerably closer to the ground, averaging about 0.55 m; and white pine, as expected, keeps its branches on the bole almost to the ground, with a mean of about 0.10 m. Pruning is determined by such factors as early limb death, susceptibility to decay and vulnerability of the branch to physical damage. Loblolly pine is usually thought of as more tolerant than Virginia pine or shortleaf pine and yet it has pruned more rapidly than those two species in this study. Possible explanations are that loblolly branches decay more rapidly once they die or that loblolly is genetically a better pruner. The limbiness of Virginia pine has long been observed, so that it is no surprise that tough, undecayed branch stubs persist far down its trunks. Resistance to decay seems to be the mechanism preventing branch shed in this species. The review of literature indicates that white pine is a notoriously slow pruner and these results are confirmed. Factors involved probably include genetics and protection from wind damage by the dense crowns.

Volume and basal area, both per tree and per hectare, are so closely related that they can be discussed together. Since both are very dependent on dbh (as evidenced by their high correlations to dbh), almost everything said about dbh applies to them, too. Per tree values increase as spacing widens and per hectare values fall. Per tree values vary directly with individual tree diameters but when mean values are expanded to per hectare estimates, the sheer numbers of trees on the narrow spacings outweigh the individually much larger but many fewer trees on the wide spacings. Loblolly pine and white pine are clearly the greater producers of wood volume by any measure. White pine almost matches the individually larger loblolly pine in volume production per hectare because of its greater survival rates at all spacings.

The number of branches per whorl in white pine does not appear to be influenced by spacing. There is, however, a significant block effect. If, as indicated, branch number is influenced by site quality, this block effect may be evidence of such an influence.

The small but significant increase in branch diameter as spacing increases is another indication of increasing vigor as competition intensity declines. However, a 0.75 cm average decline in branch diameter could hardly be expected to offset the loss of over 6 cm of dbh going from 15' by 15' to 6' by 6', however more economical the decline in branch size made artificial pruning. The small difference makes the true practical significance of this effect doubtful.

Only species showed a significant influence on survival rates; spacing had no effect. It is likely that, had not shortleaf pine experienced very heavy mortality in certain of its plots, there would have been no differences in survival rate among species. Survival for all species, including shortleaf if the problem plots were ignored, was above 70%. The small differences among species in survival is possibly accounted for by replanting, conducted after one growing season.

Block Effect

Many parameters showed significant block effects in separate analysis. In most cases, however, dbh was not influenced by block. DBH is the measurement which is easiest to obtain and is usually the most consistent. It is likely that block effect can be accounted for by experimental error.

Aggregation Of Values Into Spacing Groups

In many characteristics, especially among Virginia pines and shortleaf pines, there is a tendency for the means of measured parameters to aggregate into spacing groups. This aggregation usually takes the form of the mean values for trees planted at 6' by 6' and 9' by 9' showing less difference than that between values for trees planted at 9' by 9' and 12' by 12'. This gap is then followed by a grouping of values for trees planted at 12' by 12' and 15' by 15'. This pattern is distinct in total height among Virginia and white pines; in dbh among shortleaf pines; in height to the first live branch and percent live crown in shortleaf and Virginia pine; in crown radius among white and shortleaf pines; in basal area per tree in shortleaf pine; in basal area per hectare among shortleaf and Virginia pines; and in volume per hectare among shortleaf and Virginia pines. For most of these, it seems that a tendency to aggregate mean values into spacing groupings indicates sensitivity to crowding.

White pine shows a steady increase in mean values as spacing increases up to 12' by 12', but the values for the two widest spacings are not very widely separated. Trees at the widest spacings have not yet shown the effects of differential competition in these two parameters. Thus, as far as height and crown radius are concerned, 16-year-old white pine at 12' by 12' and 15' by 15' compete at about the same level of intensity.

For shortleaf pine and Virginia pine, a different pattern emerges. There are two groupings of means, one at the narrow end of the spacing scale, one at the wide end. The implications of the wide-end groupings are the same as for white pine--competitive pressures at the two wider spacings are less than those found between 9' by 9' and 12' by 12'. Whereas in white pine, a steady increase in values was observed as spacing increased up to 12' by 12' in shortleaf and Virginia pine there is a slight increase in values from 6' by 6' to 9' by 9', then a large increase from 9' by 9' to 12' by 12'. This suggests greater sensitivity to crowding in shortleaf and Virginia pine over loblolly and white pine. Trees planted at 6' by 6' rapidly reached a level of competition at which their growth rate fell behind those planted at wider spacings. Trees planted at 9' by 9' reached this level of competition soon after those at 6' by 6' while the trees at the wider spacings continued to grow rapidly, leaving the trees at the narrow spacings behind in a grouping. This tendency is clearly illustrated not only in declining growth rates of such parameters as dbh and volume but in the rate of lower limb death.

The pattern of grouping is the same in height to live crown in shortleaf and Virginia pine as it is in the "growth" parameters discussed above. This parameter, so obviously determined by spacing, be the agency lower light intensity or increased root competition, illustrates by analogy the agency at work in this aggregation trend. The theory is further strengthened by the fact that the trend is most easily observed in the two species considered most intolerant to shading. In loblolly pine, more tolerant than Virginia or shortleaf pine, mean values climb steadily as spacing widens, demonstrating its higher tolerance for competitive pressures. The tolerant white pine behaves similarly. It could be projected that, as time passes, first loblolly and finally white pine planted at 9' by 9' will reach a level of competition which will cause them to fall behind the trees planted at the wider spacings into wide/narrow spacing groups.

Correlated Variables

Aside from crown radius and dbh, the origins of the high correlations occurring among variables in this study can be explained mathematically. The highest correlations occur between dbh and basal area per tree (r =0.98), dbh and volume per tree (r = 0.93) and volume per hectare with basal area per hectare (r = 0.99). DBH is an important factor in the calculation of basal area and volume; volume per hectare may be looked on as basal area per hectare multiplied by one additional variable (height) and a constant. High correlations are to be expected. The calculation of percent live crown from height to live crown causes their strong association. Total height, another component of volume per tree is only moderately correlated with that variable (r = 0.67) because of the greater magnitude of the influence of dbh in that calculation. The mild correlation of dbh and total height (r = 0.56) is a reflection of the relatively small effect of spacing on total height as compared to dbh.

The amount of growth possible for a tree is dependent on many factors such as length of growing season and available moisture. It can hardly be disputed that the amount of photosynthate available to the tree is a basic determinant of its growth. Photosynthetic production is linked to the amount of photosynthetic surface or crown size. It is not surprising, then, that growth as measured by dbh is highly correlated with crown size, measured by crown radius (r = 0.75). Both dbh and crown size increase steadily as spacing widens, as does percent live crown. This increase in crown size as spacing widens is attributable to increasing levels of available light for lower branch retention. Increasing crown size with widening spacing is a source of the strong response of dbh, specifically, and growth in general, to that same widening spacing. Thus, the persistance of the crown at lower levels among trees planted at wider spacings could contribute to larger diameters at those spacings.

Overview

The response of these species of pine at 16 years of age to different initial spacings is sufficiently similar enough to consider them together to illustrate the changes that occur as spacing widens.

At narrow spacing, a slender tree with a relatively short, narrow crown is produced. Crown closure has occurred some time ago and competition for light and moisture is becoming intense. Brush and ground cover has already or is rapidly dying back. These trees at the narrow spacing are producing a large volume of wood, but this wood is distributed over very many small stems. As spacing widens the height to first live branch becomes smaller and the crown spreads and becomes larger. Among the white pines, branch diameter increases slightly. At the widest spacing, crown closure has not yet taken place and may not occur for a few years. Though the trees individually are much larger than those on the narrower spacings, they produce much less volume per hectare. Brush is still heavy and movement through the stand is difficult.

The primary agency at work creating the changes in these pines as spacing widens is competitive intensity, mainly in the form of competition for light. The fewer trees there are per unit area and the further apart they are from each other, the more light and moisture there is available for each individual. Each tree expands as a result of this increasing bounty of resources: boles thicken, branches lengthen and thicken, and crowns expand.

Large, fast-growing trees are desirable because they reduce investment and increase return. Not all aspects of increated growth on wide spacings is advantageous. Production of a clear bole is inhibited by wide spacing and knots tend to be larger in trees grown at such a spacing.

Economic analysis should aid the manager in his determination of optimum spacing.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

It is the conclusion of the author that loblolly pine and white pine are the species of choice for rapid return of investment for plantations on the Highland Rim of Tennessee. Either species can be grown to small sawtimber size on a wide spacing in 20 to 25 years; loblolly will produce a high total volume of fiber per hectare at dense spacings and grow to pulp size in less than 20 years. Pruning will be necessary on white pine grown at any spacing. The review of literature indicates that the operation will be economically sound, especially if the spacing is wide. Neither Virginia pine nor shortleaf pine, due to slow growth of both species, can be recommended for planting.

It is suggested that, after four or five more growing seasons, the study be measured again so that progress may be examined. It is further recommended that a measure of form be taken at that time so that a more accurate and applicable volume formula can be constructed for each species in the study. In addition, economic analysis should be undertaken to compare investment and return of the species at the varying spacings for different product goals and market conditions.

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APPENDIX

TABLE A-1

Summary Of Significant Effects, Combined Analysis

Parameter	Species	Block	Spacing	Species x Spacing
Total Height	*	ns	*	*
DBH	*	ns	*	*
Height To First Live Branch	*	ns	*	*
Height To First Remaining Branch	*	ns	*	*
Crown Radius	*	ns	*	*
Basal Area Per Tree	*	ns	*	*
Basal Area Per Hectare	*	ns	*	ns
Volume Per Tree	*	ns	*	*
Volume Per Hectare	*	ns	*	ns
Branch Number	-	*	ns	-
Branch Diameter	-	*	*	-
Percent Live Crown	ns	ns	*	*
Survival	*	ns	ns	ns

* Significant at $\alpha = 0.05$ ns= Not Significant

TABLE A-2

Condensed ANOVA For Loblolly Pine, Separate Analysis

Parameter	Effect	DF	MS
Total Height	Spacing	3	9.395*
	Block	3	15.065*
DBH	Spacing	3	1253.818*
	Block	3	225.046*
Height To First Live Branch	Spacing	3	321.527*
	Block	3	24.349*
Height To First Remaining Branch	Spacing	3	0.600ns
	Block	3	0.620*
Crown Radius	Spacing	3	61.293*
	Block	3	6.598*
Basal Area Per Tree	Spacing	3	0.013*
	Block	3	0.002*
Volume Per Tree	Spacing	3	0.482*
	Block	3	0.111*
Percent Live Crown	Spacing	3	18548.878*
	Block	3	1520.686*

* Significant at $\alpha = 0.05$ ns = Not Significant

TABLE A-3

Duncan's Multiple Range Tests For Loblolly Pine, Separate Analysis

Parameter	Spacing	Mean*
Total Height (m)	6' by 6'	12.59 A
	9' by 9'	12.95 A,B
	12' by 12'	12.73 A,B
	15' by 15'	12.33 B
DBH (cm)	6' by 6'	16.04 A
	9' by 9'	18.90 B
	12' by 12'	21.09 C
	15' by 15'	23.23 D
Height To First Live Branch (m)	6' by 6'	7.37 A
	9' by 9'	6.66 B
	12' by 12'	5.43 C
	15' by 15'	3.81 D
Percent Live Crown	6' by 6'	41.0 A
	9' by 9'	48.0 B
	12' by 12'	56.8 C
	15' by 15'	68.4 D
Crown Radius (m)	6' by 6'	1.20 A
	9' by 9'	1.67 B
	12' by 12'	2.20 C
	15' by 15'	2.77 D
Basal Area Per Tree (m^2)	6' by 6'	0.021 A
	9' by 9'	0.030 B
	12' by 12'	0.037 C
	15' by 15'	0.045 D
Volume Per Tree (m^3)	6' by 6'	0.138 A
	9' by 9'	0.195 B
	12' by 12'	0.236 C
	15' by 15'	0.279 D

* Values with the same letter are not significantly different at $\alpha = 0.05$.

TABLE A-4

Condensed ANOVA For Shortleaf Pine, Separate Analysis

Parameter	Effect	DF	MS
Total Height	Spacing	3	44.219*
	Block	3	17.472*
DBH	Spacing	3	300.248*
	Block	3	182.694*
Height To First Live Branch	Spacing	3	129.680*
	Block	3	43.243*
Height To First Remaining Branch	Spacing	3	0.456ns
	Block	3	3.071*
Crown Radius	Spacing	3	9.203*
	Block	3	8.227*
Basal Area Per Tree	Spacing	3	0.002*
	Block	3	0.001*
Volume Per Tree	Spacing	3	0.029*
	Block	3	0.023*
Percent Live Crown	Spacing	3	7457.257*
	Block	3	4658.365*

* Significant at $\alpha = 0.05$ ns = Not Significant

TABLE A-5

Duncan's Multiple Range Tests For Shortleaf Pine, Separate Analysis

Parameter	Spacing	Mean*
Total Height (m)	6' by 6'	10.38 A
	9' by 9'	10.02 A
	12' by 12'	9.62 B
	15' by 15'	9.04 C
DBH (cm)	6' by 6'	13.51 A
	9' by 9'	13.83 A
	12' by 12'	16.08 B
	15' by 15'	16.56 B
Height To First Live Branch (m)	6' by 6'	5.36 A
	9' by 9'	4.72 B
	12' by 12'	3.35 C
	15' by 15'	3.29 C
Percent Live Crown	6' by 6'	48.0 A
	9' by 9'	52.3 B
	12' by 12'	64.2 C
	15' by 15'	62.7 C
Crown Radius (m)	6' by 6'	1.19 A
	9' by 9'	1.32 A
	12' by 12'	1.78 B
	15' by 15'	1.64 B
Basal Area Per Tree (m^2)	6' by 6'	0.015 A
	9' by 9'	0.016 A
	12' by 12'	0.021 B
	15' by 15'	0.023 B
Volume Per Tree (m^3)	6' by 6'	0.079 A
	9' by 9'	0.084 A
	12' by 12'	0.112 B
	15' by 15'	0.099 C

* Values with the same letter are not significantly different at $\alpha = 0.05$.

TABLE A-6

Condensed ANOVA For Virginia Pine, Separate Analysis

Parameter	Effect	DF	MS
Total Height	Spacing	3	96.151*
	Block	3	9.199*
DBH	Spacing	3	659.454*
	Block	3	20.107ns
Height To First Live Branch	Spacing	3	579.420*
	Block	3	2.034ns
Height To First Remaining Branch	Spacing	3	1.419*
	Blcok	3	1.237*
Crown Radius	Spacing	3	60.566*
	Block	3	1.813*
Basal Area Per Tree	Spacing	3	0.004*
	Block	3	0.000ns
Volume Per Tree	Spacing	3	0.064*
	Block	3	0.002ns
Percent Live Crown	Spacing	3	38417.600*
	Block	3	702.243*

* Significant at $\alpha = 0.05$ ns = Not Significant

TABLE A-7

Duncan's Multiple Range Tests For Virginia Pine, Separate Analysis

Parameter	Spacing	Mean *
Total Height (m)	6' by 6'	11.50 A
	9' by 9'	10.74 B
	12' by 12'	9.49 C
	15' by 15'	9.67 C
DBH (cm)	6' by 6'	13.04 A
	9' by 9'	15.42 B
	12' by 12'	17.84 C
	15' by 15'	18.61 D
Height To First Live Branch (m)	6' by 6'	6.57 A
	9' by 9'	4.86 B
	12' by 12'	2.47 C
	15' by 15'	1.77 D
Percent Live Crown	6' by 6'	42.3 A
	9' by 9'	54.4 B
	12' by 12'	73.1 C
	15' by 15'	81.1 D
Height To First Remaining Branch (m)	6' by 6'	0.61 A,B
	9' by 9'	0.57 B
	12' by 12'	0.66 A
	15' by 15'	0.44 C
Crown Radius (m)	6' by 6'	1.12 A
	9' by 9'	1.77 B
	12' by 12'	2.41 C
	15' by 15'	2.75 D
Basal Area Per Tree (m^2)	6' by 6'	0.014 A
	9' by 9'	0.022 B
	12' by 12'	0.026 C
	15' by 15'	0.028 D
Volume Per Tree (m^3)	6' by 6'	0.080 A
	9' by 9'	0.117 B
	12' by 12'	0.123 B
	15' by 15'	0.136 C

* Values with the same letter are not significantly different at $\alpha = 0.05$.

TABLE A-8

Condensed ANOVA For Eastern White Pine, Separate Analysis

Parameter	Effect	DF	MS
Total Height	Spacing	3	22.486*
	Block	3	30.384*
DBH	Spacing	3	1213.916*
	Block	3	21.449*
Height To First Live Branch	Spacing	3	330.436*
	Block	3	48.447*
Height To First Remaining Branch	Spacing	3	0.190*
	Block	3	0.264*
Crown Radius	Spacing	3	40.339*
	Block	3	4.729*
Branch Number	Spacing	3	2.330ns
	Block	3	38.273*
Branch Diameter	Spacing	3	13.416*
	Block	3	2.259*
Basal Area Per Tree	Spacing	3	0.010*
	Block	3	0.000ns
Volume Per Tree	Spacing	3	0.385*
	Block	3	0.011ns
Percent Live Crown	Spacing	3	31120.230*
	Block	3	2476.834*

* Significant at $\alpha = 0.05$ ns = Not Significant

TABLE A-9

Duncan's Multiple Range Tests For Eastern White Pine, Separate Analysis

Parameter	Spacings	Mean*
Total Height (m)	6' by 6'	10.96 A
	9' by 9'	11.20 A
	12' by 12'	11.75 B
	15' by 15'	11.75 B
DBH (cm)	6' by 6'	14.04 A
	9' by 9'	16.29 B
	12' by 12'	18.65 C
	15' by 15'	20.86 D
Height To First Live Branch (m)	6' by 6'	5.98 A
	9' by 9'	5.27 B
	12' by 12'	4.08 C
	15' by 15'	2.47 D
Percent Live Crown	6' by 6'	44.9 A
	9' by 9'	52.4 B
	12' by 12'	64.7 C
	15' by 15'	79.0 D
Height to First Remaining Branch (m)	6' by 6'	0.13 A
	9' by 9'	0.05 B
	12' by 12'	0.12 A,C
	15' by 15'	0.06 B,C
Crown Radius (m)	6' by 6'	1.19 A
	9' by 9'	1.59 B
	12' by 12'	2.03 C
	15' by 15'	2.43 D
Basal Area Per Tree (m^2)	6' by 6'	0.017 A
	9' by 9'	0.023 B
	12' by 12'	0.030 C
	15' by 15'	0.036 D
Volume Per Tree (m^3)	6' by 6'	0.098 A
	9' by 9'	0.140 B
	12' by 12'	0.185 C
	15' by 15'	0.218 D

TABLE A-9 (continued)

Parameter	Spacing	Mean*
Branch Diameter (cm)	6' by 6'	1.94 A
	9' by 9'	2.28 B
	12' by 12'	2.22 C
	15' by 15'	2.69 D

* Values with the same letter are not significantly different at $\alpha = 0.05$.

TABLE A-10

Condensed ANOVAs, Combined Analysis

Parameter	Effect	DF	MS
Total Height	Species	3	866.293*
	Block	3	31.063ns
	Spacing	3	48.227*
	Spacing x Species	9	45.303*
DBH	Species	3	2104.487*
	Block	3	137.977ns
	Spacing	3	2968.705*
	Spacing x Species	9	104.551*
Height To First Live Branch	Species	3	384.142*
	Block	3	45.305ns
	Spacing	3	1215.106*
	Spacing x Species	9	38.320*
Height to First Remaining Branch	Species	3	239.188*
	Block	3	2.795ns
	Spacing	3	0.599*
	Spacing x Species	9	0.688*
Crown Radius	Species	3	29.301*
	Block	3	9.312ns
	Spacing	3	145.504*
	Spacing x Species	9	6.223*
Basal Area Per Tree	Species	3	0.019*
	Block	3	0.001ns
	Spacing	3	0.023*
	Spacing x Species	9	0.001*
Basal Area Per Hectare	Species	3	715.680*
	Block	3	52.449ns
	Spacing	3	1788.890*
	Spacing x Species	9	14.818ns
Volume Per Tree	Species	3	1.452*
	Block	3	0.033ns
	Spacing	3	0.671*
	Spacing x Species	9	0.072*

TABLE A-10 (continued)

Parameter	Effect	DF	MS
Volume Per Hectare	Species	3	40745.373*
	Block	3	2175.137ns
	Spacing	3	62617.273*
	Spacing x Species	9	942.813ns
Survival	Species	3	0.326*
	Block	3	0.143ns
	Spacing	3	0.022ns
	Spacing x Species	9	0.036ns
Percent Live Crown	Species	3	8342.902ns
	Block	3	1976.443ns
	Spacing	3	82829.583*
	Spacing x Species	9	2975.941*

* Significant at $\alpha = 0.05$ ns = Not Significant

TABLE A-11

Duncan's Multiple Range Test For Basal Area Per Hectare, Combined Analysis, Spacing

Spacing	Mean*
6' by 6'	36.59 A
9' by 9'	23.27 B
12' by 12'	15.35 C
15' by 15'	11.47 C

* Values with the same letter are not significantly different at $\alpha = 0.05$.

TABLE A-12

Duncan's Multiple Range Test For Basal Area Per Hectare, Combined Analysis, Species

Species	Mean*
Loblolly	28.40 A
White	25.52 A
Virginia	18.12 B
Shortleaf	13.48 C

* Values with the same letter are not significantly different at $\alpha = 0.05$.

TABLE A-13

Duncan's Multiple Range Test For Volume Per Hectare, Combined Analysis, Spacing

Spacing	Mean*
6' by 6'	214.79 A
9' by 9'	137.00 B
12' by 12'	89.94 C
15' by 15'	65.27 D

* Values with the same letter are not significantly different at $\alpha = 0.05$.

TABLE A-14

Duncan's Multiple Range Test For Volume Per Hectare, Combined Analysis, Species

Species	Mean*
Loblolly	182.85 A
White	151.19 B
Virginia	96.11 C
Shortleaf	69.44 D

* Values with the same letter are not significantly different at $\alpha = 0.05$.

TABLE A-15

Duncan's Multiple Range Test For Survival, Combined Analysis

Species	Mean*
White	1.18 (85.1%) A
Loblolly	1.06 (75.9%) A
Virginia	1.02 (72.4%) A,B
Shortleaf	0.84 (55.5%) B

* Values with the same letter are not significantly different at $\alpha = 0.05$.

Mean values are results of the operation Arcsin $\sqrt{Y_i}$ on the the equivalent percent value given in parentheses. These results should be viewed with caution since the data only approximated a normal distribution.

TABLE A-16

Correlation Matrix For Combined Analysis

Parameter	TH	DBH	LC	P	CR	BA	V	PLC
TH	1.0	.56	.43	.15	.25	.53	.68	.02
DBH		1.0	-.17	.10	.75	.98	.94	.46
LC			1.0	.22	-.47	-.18	-.05	-.87
P				1.0	-.01	.10	.13	-.16
CR					1.0	.73	.65	.66
BA						1.0	.97	.45
V							1.0	.36
PLC								1.0

TH = Total Height
DBH = Diameter Breast Height
LC = Height to First Live Branch
P = Height to First Remaining Branch
CR = Crown Radius
BA = Basal Area per Tree
V = Volume per Tree
PLC = Percent Live Crown

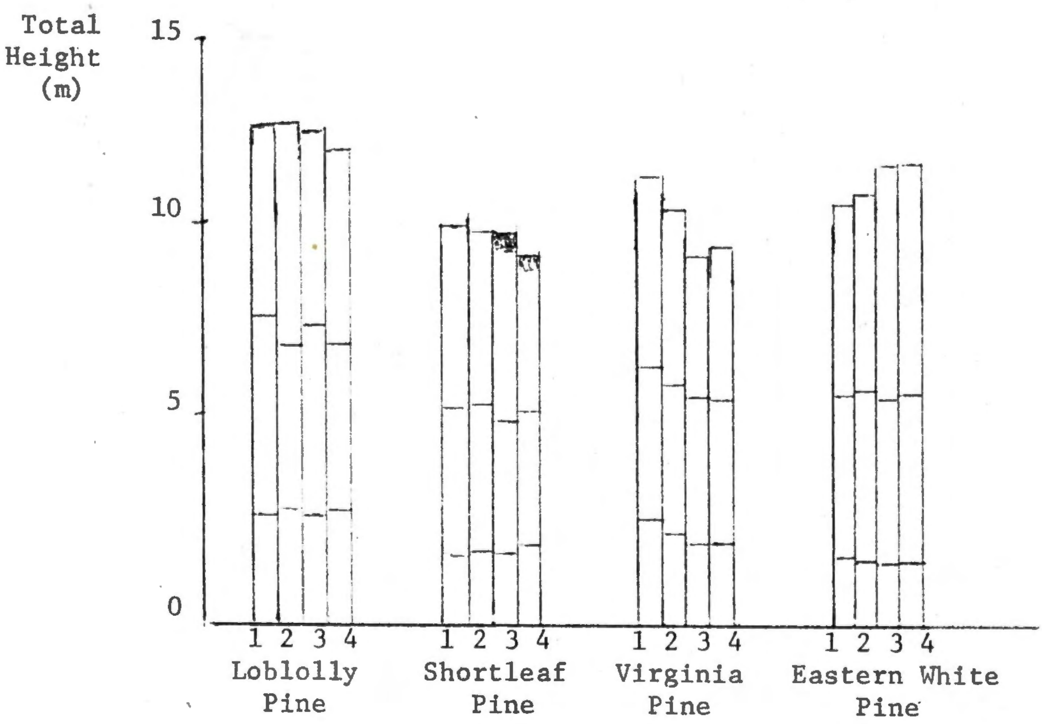

Figure A-1. Mean total height over spacing by age and species.

Numbers denote spacing widths: (1) 6' by 6'; (2) 9' by 9'; (3) 12' by 12'; (4) 15' by 15'. The first division in the bar denotes 10 year data; the second denotes 16 year data; a third, dark division denotes shortleaf pine without problem plot data.

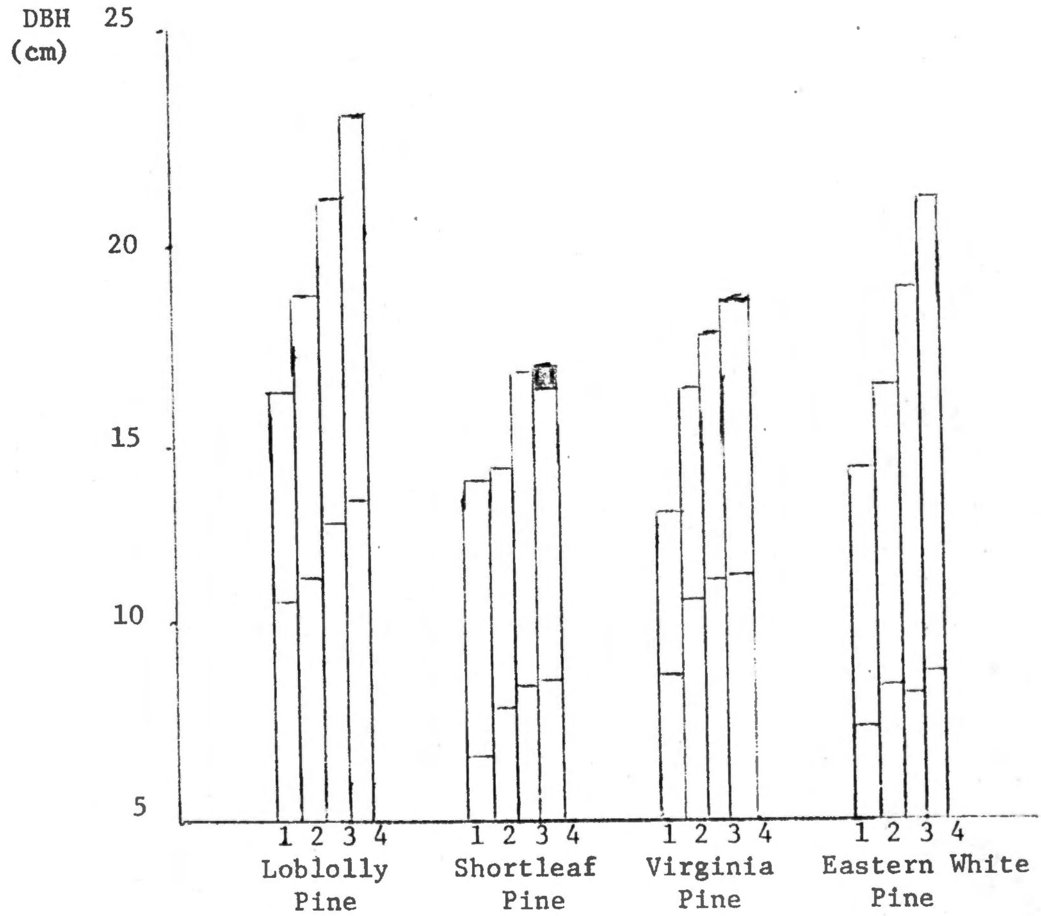

Figure A-2. Mean DBH over spacing by age and species.

Numbers denote spacing widths: (1) 6' by 6'; (2) 9' by 9'; (3) 12' by 12'; (4) 15' by 15'. The first division in the bar denotes 10 year data; the second denotes 16 year data; a third, dark division denotes 16 year shortleaf pine without problem plot data.

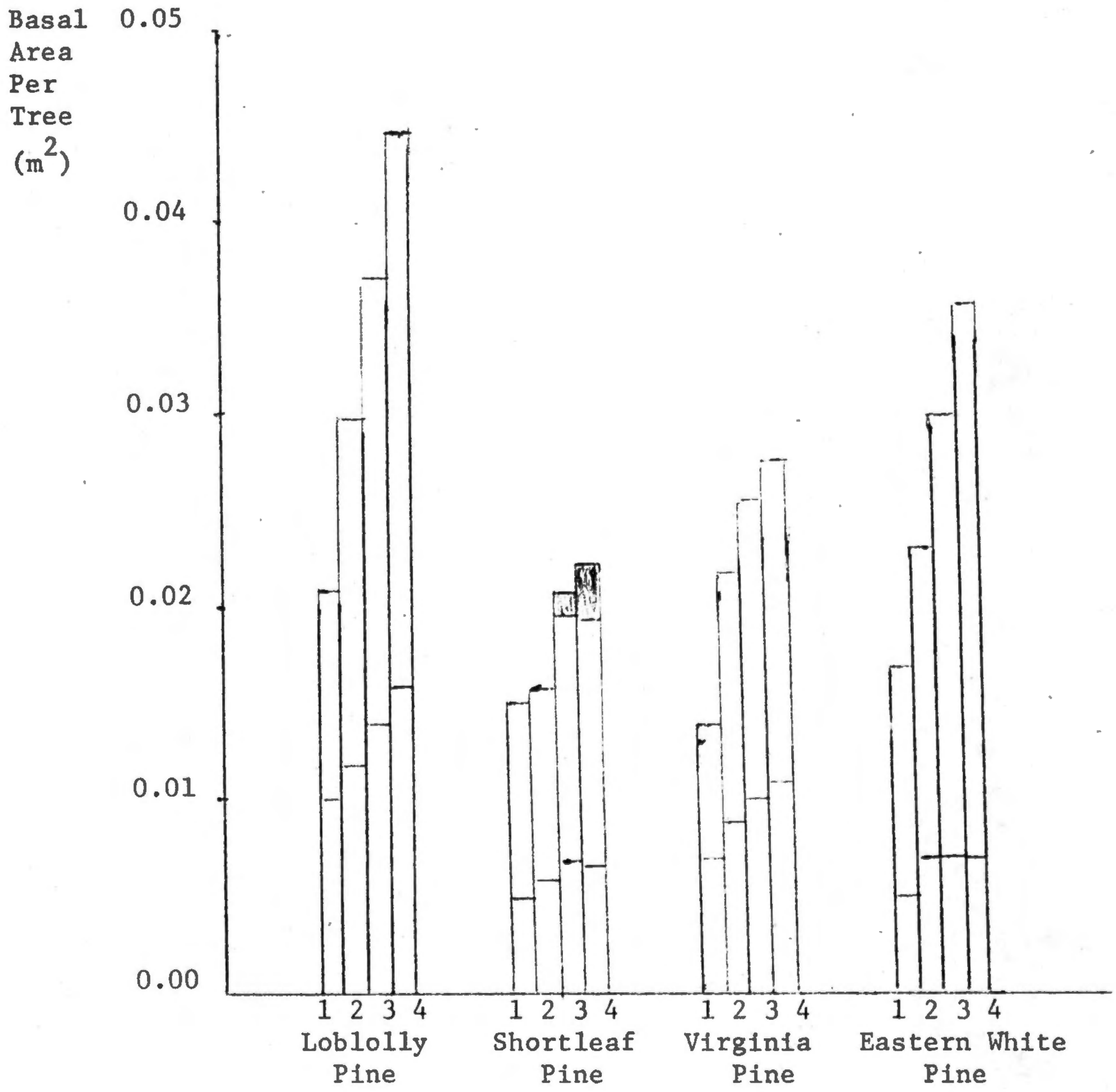

Figure A-3. Mean basal area per tree over spacing by age and species.

Numbers denote spacing widths: (1) 6' by 6'; (2) 9' by 9'; (3) 12' by 12'; (4) 15' by 15'. The first division in the bar denotes 10 year data; the second denotes 16 year data; a third, dark division denotes 16 year shortleaf pine without problem plot data.

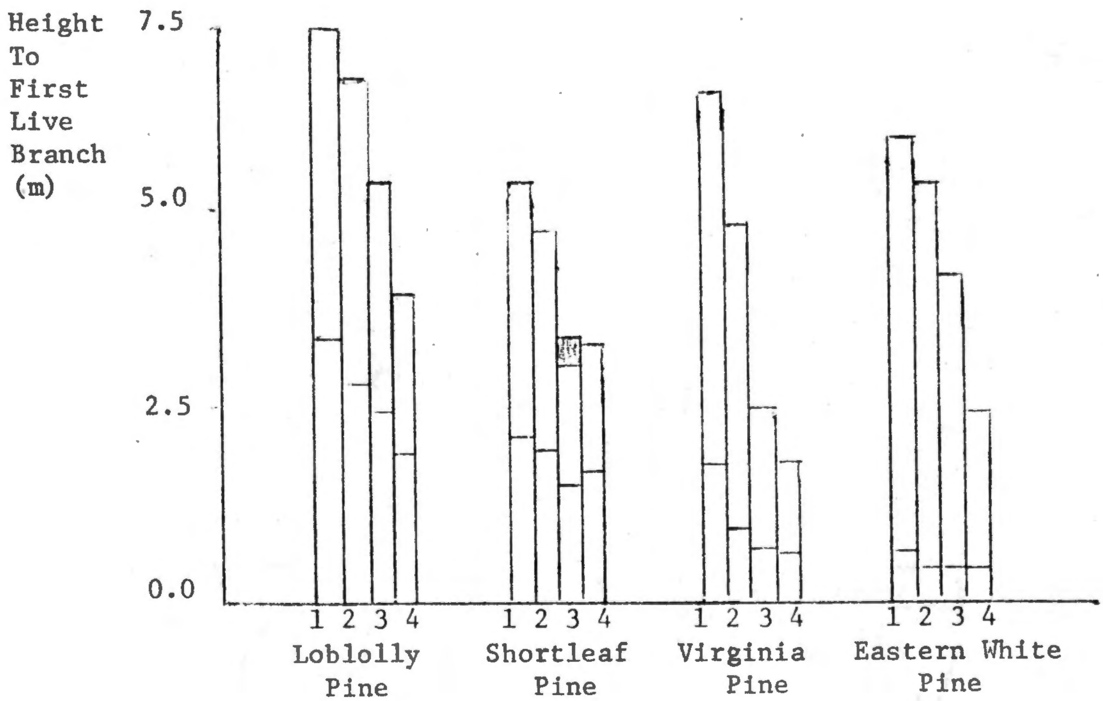

Figure A-4. Mean height to first live branch over spacing by age and species.

Numbers denote spacing widths: (1) 6' by 6'; (2) 9' by 9'; (3) 12' by 12'; (4) 15' by 15'. The first division in the bar denotes 10 year data; a third, dark division denotes 16 year shortleaf pine without problem plot data.

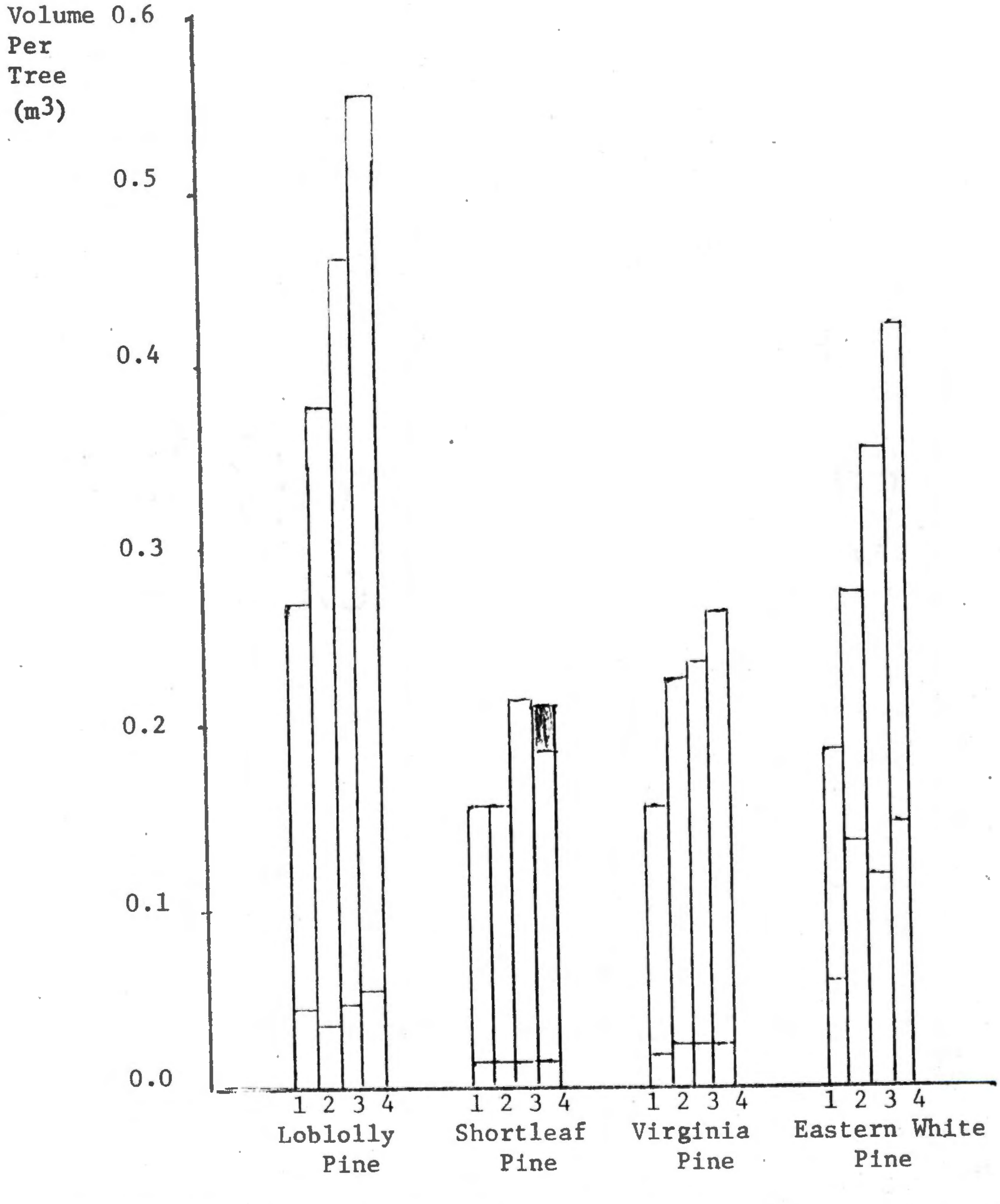

Figure A-5. Mean volume per tree over spacing by age and species.

Numbers denote spacing widths: (1) 6' by 6'; (2) 9' by 9'; (3) 12' by 12'; (4) 15' by 15'. The first division in the bar denotes 10 year data; the second denotes 16 year data; a third, dark division denotes 16 year shortleaf pine data without problem plot data.

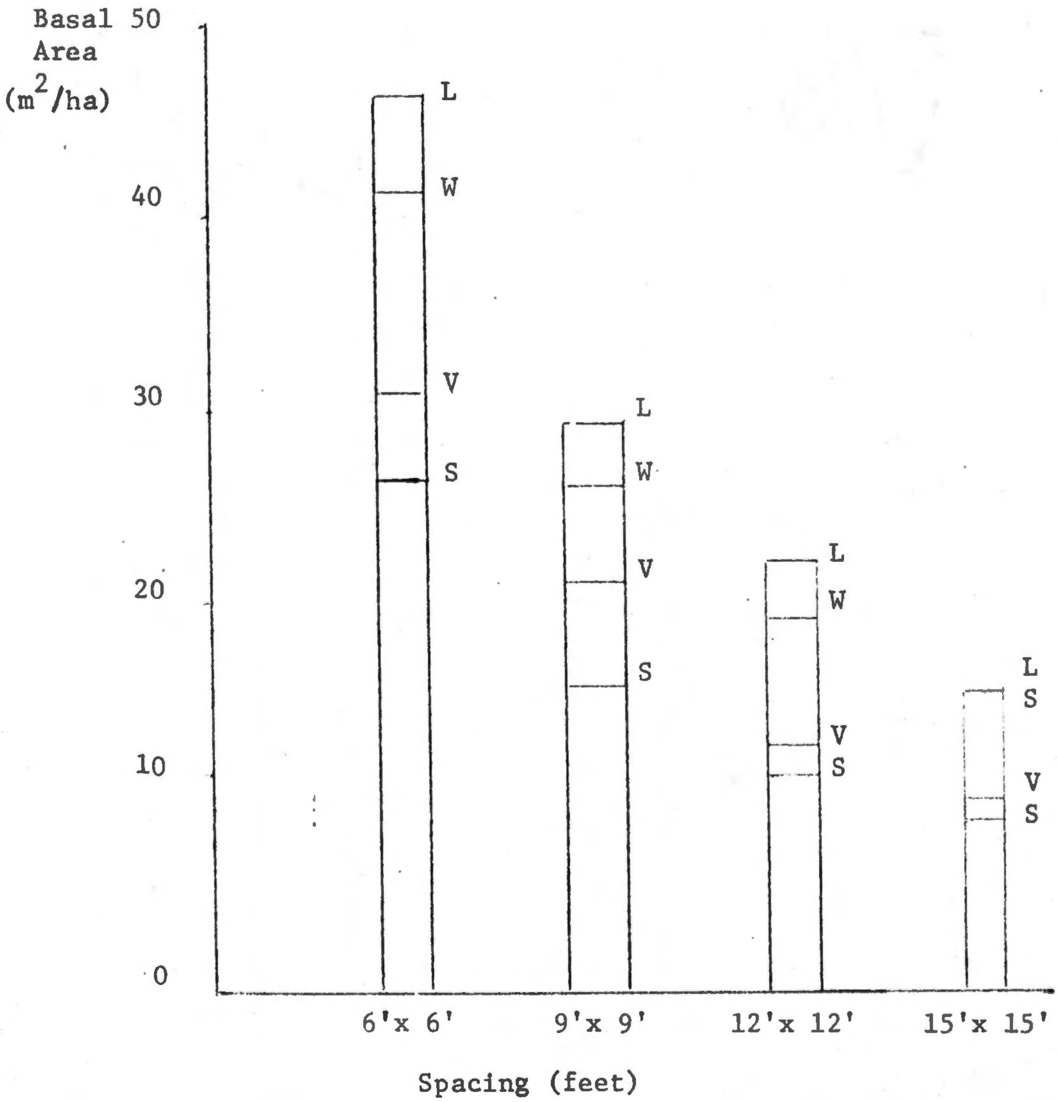

Figure A-6. Mean basal area per hectare over spacing by species at age 16.

L-Loblolly Pine; W-Eastern White Pine; V-Virginia Pine; S-Shortleaf Pine.

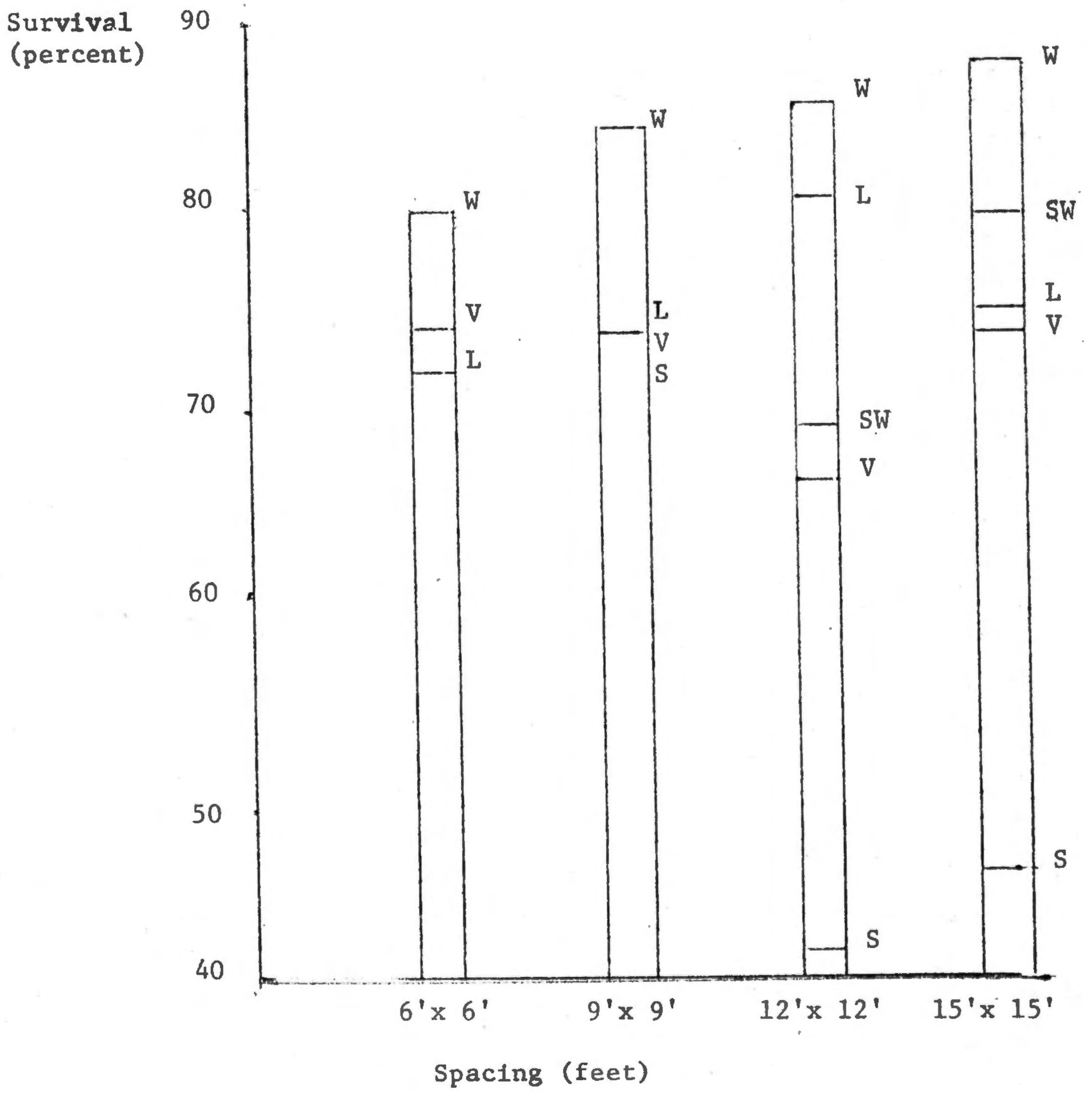

Figure A-7. Mean survival percentage over spacing by species at age 16.

W-Eastern White Pine; V-Virginia Pine; L-Loblolly Pine; S-Shortleaf Pine; SW-Shortleaf Pine without problem plot data.

VITA

David Clayton Miller was born in Maryville, Tennessee on December 3, 1956. He attended elementary schools in that city and was graduated from Maryville High School in 1974. The following August he entered Newberry College, Newberry, South Carolina, and received the Bachelor of Arts degree in Political Science and Speech-Theatre in 1978.

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The author is a member of Xi Sigma Pi and The Society of American Foresters.