Rotation-Age Results from a Loblolly Pine Spacing Trial

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ABSTRACT

This study reports cubic-foot volume yields for particular product definitions from a 25-year-old loblolly pine spacing trial and shows how closely, in the absence of thinning, total and merchantable wood production are linked to initial spacing. Results at the close of the study indicate that (1) high-density plantations can be managed on short rotations for woody biomass production; (2) pulpwood yields can be maximized at a planting density in the neighborhood of 680 trees/ac; (3) the production of solidwood products, without imposing thinning, requires lower establishment densities, with as few as 300 trees/ac planted resulting in a substantial proportion of the total yield recovered as large sawtimber; and (4) a ratio of between-row to within-row planting distances of at least 3:1 does not substantially affect yield production. Considered together, the results of this study suggest that no single planting density is optimal for the wide array of product objectives for which loblolly pine is managed in the South. Rather, managers must select an appropriate planting density in view of the products anticipated at harvest.

Keywords: growth and yield, density, spacing, *Pinus taeda* L.

Few decisions have a greater impact on the growth and development of loblolly pine plantations than how many trees are planted per acre. Managers know that planting density will affect the quantity and quality of wood harvested at rotation, as well as the type and timing of intermediate silvicultural treatments.

Given the importance of initial spacing on the growth and development of forest stands, spacing trials have been established for many tree species. Evert (1971) published a comprehensive review of many spacing studies established where plantation forestry is practiced. He noted that results from many of these studies were limited because of inadequacies in the definition of study objectives, the experimental design, the longevity of the study, or the measurements collected. For loblolly pine, two of the better known studies with at least 25 years of history are the Hawaii spacing trial on the island of Maui and the Calhoun Experimental Forest trial in South Carolina (Harms et al. 1994).

In an effort to increase understanding of how loblolly pine plantations grow in the southern United States, a set of loblolly pine spacing trials was established at four sites in Virginia and North Carolina in the spring of 1983. The primary goals for the study were to (1) evaluate the effects of spacing and density on the growth, development, and survival of loblolly pine trees; (2) provide data for modeling growth and yield relationships; and (3) determine the optimal (in a biological or growth and yield sense) planting densities for particular product objectives. This report presents results related to goal 3 of the study. Yield in relation to four definitions of stand volume was analyzed, namely stand volume and volume of all trees above a specified threshold diameter limit for pulpwood, chip-and-saw, and sawtimber utilization.

The Study

Design and Field Procedures

The experimental design for the study was the nonsystematic design presented by Lin and Morse (1975) in which plots of different sizes and shapes containing equal numbers of trees fit together to form a compact block (Figure 1). Applying this design, a spacing factor (F) of 4 ft was chosen, and four levels of that factor (1F, 1.5F, 2F, and 3F) were selected and randomly assigned to row and column positions on a two-dimensional grid. The intersection of the row and column factors defined 16 plots, each with a specific spacing and density. The factorial arrangement of 16 plots, each with seven rows and seven trees within each row, made up a compact block of about 2.5 ac, including guard trees (Figure 1). Each block contained 4 square plots (4 × 4, 6 × 6, 8 × 8, and 12 × 12 ft) and 12 rectangular plots (4 × 6, 4 × 8, 4 × 12, 6 × 4, 6 × 8, 6 × 12, 8 × 4, 8 × 6, 8 × 12, 12 × 4, 12 × 6, and 12 × 8 ft). Thus, each rectangular plot had a companion plot that was the same spacing and density but shifted 90 degrees with regard to the row and column spacing (e.g., 4 × 12 ft and 12 × 4 ft have the same spacing and density, but the row direction of one is the column direction of the other). Additional details of the experimental design as applied to this study can be found in Amateis et al. (1988); Burkhart (2002) provides an overview of design options for spacing trials.

Four sites were selected, two in the Piedmont and two in the Coastal Plain (Table 1). All sites were cutover areas that had received mechanical site preparation and burning treatments following harvest. Three blocks were established at each site. In most cases, blocks at a site were contiguous, or nearly so. The planting stock used was genetically improved 1-0 loblolly pine bareroot seedlings. The two Coastal Plain sites were planted with material from Coastal Plain

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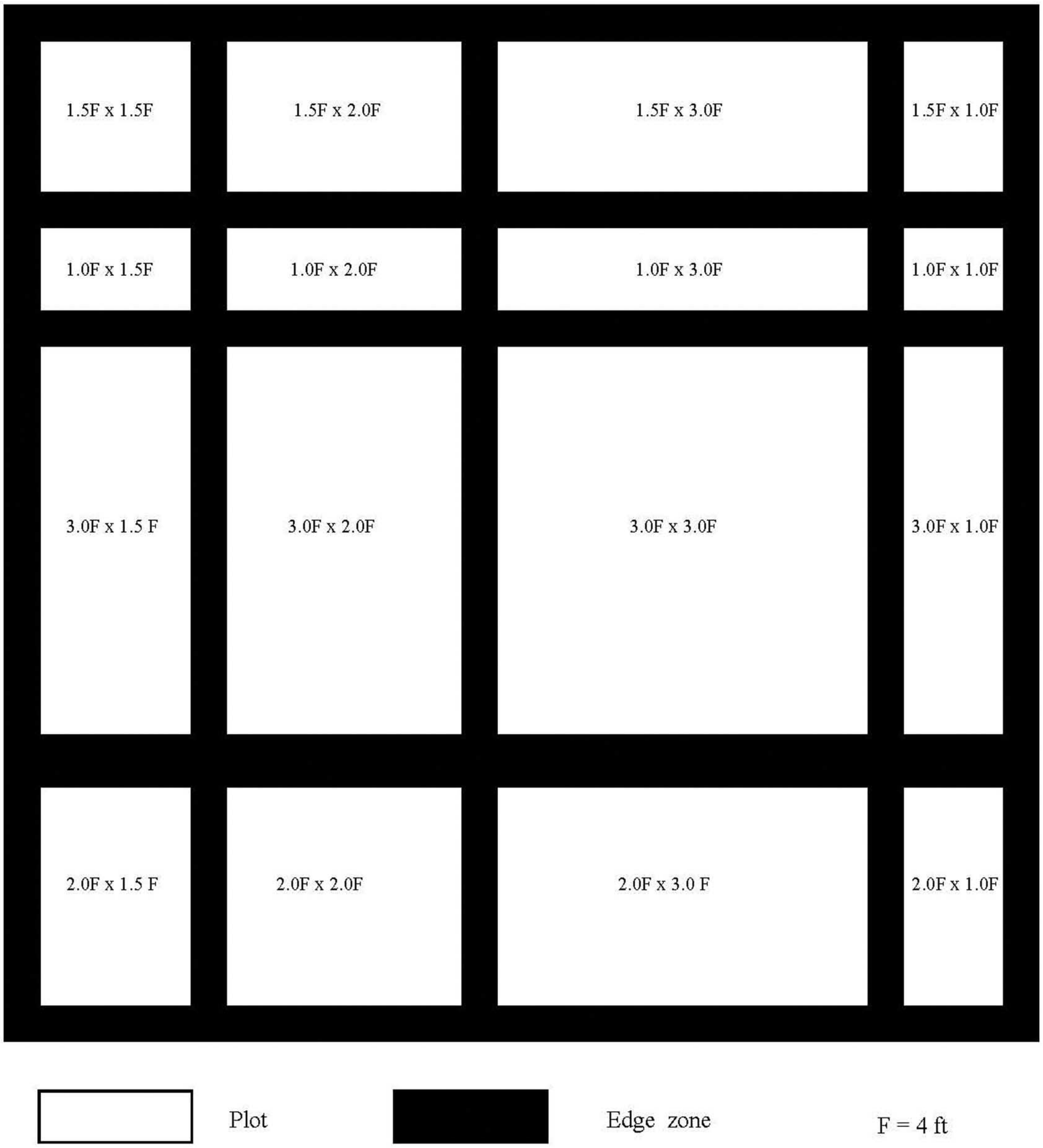

Figure 1. Example block of the loblolly pine spacing trials using the nonsystematic design of Lin and Morse (1975): 16 treatment plots with three-row buffer areas separating treatment plots. Treatment plots of different sizes each contained 49 measurement trees.

Table 1. Sites for the loblolly pine spacing trials.

Physiographic region	State	County	Latitude (N)	Longitude (W)
Piedmont	VA	Buckingham	37°26′	78°37′
Piedmont	VA	Halifax	36°45′	78°43′
Coastal plain	NC	Halifax	36°11′	77°29′
Coastal plain	VA	King and Queen	37°31′	76°43′

seed sources, and the two Piedmont sites were planted with material from Piedmont seed sources. For the first 2 years following establishment, both herbaceous and woody competing vegetation were controlled with herbicides. Otherwise, no management treatments were applied in this study.

Measurements included groundline diameter at ages 1–5 and dbh annually from age 5. Total height was measured annually through age 10 and biennially thereafter. A damage assessment code was collected annually. At age 25, crown class information was collected on all trees. No assessment of stem quality was made during the life of the study. Therefore, Table 2 presents average stand characteristics for all trees by spacing at ages 5, 10, 15, 20, and 25.

Unique features of this study include blocks established at two sites within each of two major physiographic regions, an extreme range of planting densities from 2,722 to 302 trees/ac, ratios of within-row to between-row distances varying from 1:1 to 3:1, and annual (or nearly annual) measurements from establishment to conclusion of the study (age 25).

History

Periodically over the life of the study, analyses were completed to examine the growth and development of loblolly pine under different establishment densities. Zhang et al. (1996) used data through age 10 to study the effect of spacing and density on juvenile loblolly pine plantation development. The individual tree models developed from that work can be used to predict juvenile growth of loblolly

Table 2. Mean stand characteristics by spacing at 5, 10, 15, 20, and 25 years across all locations and replications for the loblolly pine spacing trials.

	Planted spacing (ft)									
Stand variable	4 × 4	4 × 6, 6 × 4	4 × 8, 8 × 4	4 × 12, 12 × 4	6 × 6	6 × 8, 8 × 6	6 × 12, 12 × 6	8 × 8	8 × 12, 12 × 8	12 × 12
Planted (trees/ac)	2,272	1,814	1,361	908	1,210	908	605	681	454	303
Age 5										
Trees/ac	2,648	1,773	1,318	875	1,175	873	583	664	445	296
Height (ft)	12.2	12.4	12.4	12.9	12.3	12.5	12.6	12.6	12.6	12.7
Basal area (ft^2/ac)	58	46	37	29	35	29	21	24	17	12
dbh (in)	1.9	2.1	2.2	2.4	2.2	2.3	2.4	2.5	2.5	2.6
Crown ratio (%)	75	79	82	85	83	85	87	87	88	88
Total volume (ft^3/ac)[a]	860	624	482	354	439	351	243	283	194	133
Age 10										
Trees/ac	2,491	1,718	1,309	870	1,154	865	580	659	441	293
Height (ft)	27.5	28.6	29.4	30.7	29.3	30.3	31.0	31.0	31.3	31.3
Basal area (ft^2/ac)	164	146	132	115	127	116	98	107	87	71
dbh (in)	3.4	3.8	4.2	4.8	4.4	4.9	5.5	5.4	5.9	6.6
Crown ratio (%)	42	46	50	58	50	54	62	58	65	71
Total volume (ft^3/ac)[a]	2,638	2,324	2,099	1,835	1,985	1,826	1,549	1,700	1,371	1,107
Pulpwood (ft^3/ac)[b]	246	516	761	1,042	844	1,053	1,107	1,189	1,075	935
Chip-and-saw (ft^3/ac)[c]	0	0	0	0	0	9	26	18	64	221
Age 15										
Trees/ac	1,884	1,509	1,177	806	1,073	817	559	625	426	283
Height (ft)	37.6	38.3	39.7	41.6	39.8	41.5	43.0	42.6	43.5	44.2
Basal area (ft^2/ac)	190	189	179	163	172	165	149	156	137	119
dbh (in)	4.2	4.7	5.1	5.9	5.3	6.0	6.9	6.7	7.6	8.7
Crown ratio (%)	29	31	33	38	34	36	42	38	44	50
Total volume (ft^3/ac)[a]	3,793	3,743	3,616	3,357	3,459	3,402	3,114	3,249	2,871	2,504
Pulpwood (ft^3/ac)[b]	1,421	1,993	2,339	2,628	2,386	2,659	2,685	2,753	2,581	2,337
Chip-and-saw(ft^3/ac)[c]	0	0	111	479	76	381	1,017	836	1,456	1,790
Sawtimber (ft^3/ac)[d]	0	0	0	0	0	0	0	0	8	178
Age 20										
Trees/ac	1,148	1,058	878	650	733	663	500	565	395	265
Height (ft)	46.6	48.6	50.3	52.3	49.9	52.7	54.4	54.5	56.1	57.7
Basal area (ft^2/ac)	159	177	176	174	158	175	172	179	163	145
dbh (in)	4.9	5.4	5.9	6.8	6.1	6.8	7.8	7.5	8.6	9.9
Crown ratio (%)	27	27	29	32	30	30	34	32	36	42
Total volume (ft^3/ac)[a]	3,716	4,286	4,381	4,456	3,874	4,505	4,521	4,714	4,373	3,967
Pulpwood (ft^3/ac)[b]	2,234	2,995	3,390	3,839	3,111	3,867	4,104	4,222	4,075	3,791
Chip-and-saw (ft^3/ac)[c]	156	395	745	1,675	834	1,566	2,557	2,357	3,043	3,297
Sawtimber (ft^3/ac)[d]	0	0	0	109	0	90	190	120	436	1,359
Age 25										
Trees/ac	556	640	567	462	487	455	371	433	331	237
Dominant height (ft)	59.1	61.7	64.3	67.0	62.9	65.4	67.5	67.3	68.6	70.1
Height (ft)	56.3	59.2	60.3	63.4	60.5	63.0	65.5	65.1	66.9	68.9
Basal area (ft^2/ac)	128	157	163	172	148	166	168	177	171	162
dbh (in)	6.3	6.6	7.1	8.1	7.3	8.0	8.9	8.5	9.6	11.0
Crown ratio (%)	26	27	27	30	28	29	31	29	31	36
Total volume (ft^3/ac)[a]	3,536	4,515	4,800	5,250	4,330	5,009	5,224	5,514	5,394	5,233
Pulpwood (ft^3/ac)[b]	2,912	3,779	4,215	4,820	3,847	4,587	4,909	5,131	5,131	5,066
Chip-and-saw (ft^3/ac)[c]	1,214	1,270	2,196	3,253	2,092	3,038	3,794	3,694	4,276	4,593
Sawtimber (ft^3/ac)[d]	0	100	207	673	167	571	1,249	891	1,690	3,065

[a] Outside bark volume, all trees.
[b] Outside bark volume 5-in. dbh class and above to 4-in. top diameter outside bark.
[c] Outside bark volume 8-in. dbh class and above to 6-in. top diameter outside bark.
[d] Outside bark volume 11-in. dbh class and above to 8-in. top diameter outside bark.

pine plantations covering a wide range of planting densities. Using annual measurements through age 8, Liu and Burkhart (1993) determined that the distribution of tree diameters, total heights, and crown heights were significantly correlated with stand age and numbers of trees per unit area. Liu and Burkhart (1994) applied trend surface analysis of spatial characteristics of tree diameters and total heights in an effort to separate systematic microsite variation from variation incurred by intertree competition. Their results showed that in the seedling period of stand development, the systematic environmental gradients had a dominant impact on the spatial pattern of dbh and total height; however, the effect of environmental gradients diminished as stands developed. Bullock and Burkhart (2003) applied a simultaneous autoregressive model to evaluate the extent of spatial influence that stems in juvenile loblolly pine stands have on one another. Analysis of diameter measurement data indicated significant spatial dependency in 23.2% of the spacing trial plots. Diameter distributions of juvenile loblolly pine stands were characterized using the two-parameter Weibull function to gain insight into the effects of stand density and to aid in characterizing diameter distributions in juvenile loblolly pine stands (Bullock and Burkhart 2005).

Sterba and Amateis (1998) used the 10-year data to examine the relationship between basal area increment and crown efficiency and the ratio of crown surface area to crown projection area. Radtke and

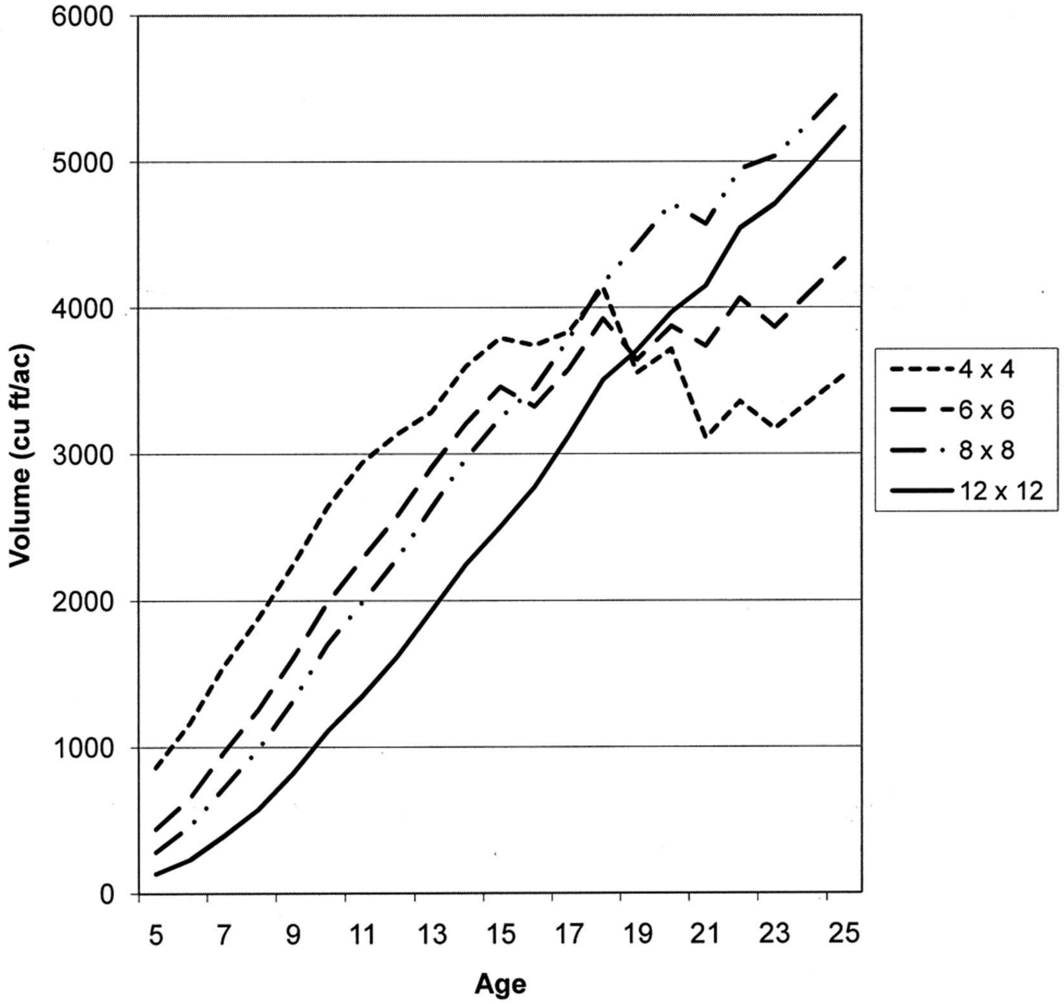

Figure 2. Total cubic-foot volume outside bark for the 4 × 4-ft, 6 × 6-ft, 8 × 8-ft, and 12 × 12-ft square spacing treatments for ages 5–25 of the loblolly pine spacing trials.

Burkhart (1999) used early data from the study to examine relationships between the inflection age of cumulative basal area growth, crown closure, and crown competition factor. Radtke et al. (2003) investigated the relationship between competition and age of inflection of individual-tree basal area curves. Results from these latter two studies provide insights into how basal area development should be modeled over the early years for different planting densities.

MacFarlane et al. (2000) examined the assumption that height growth of dominant trees is independent of initial planting density using data on the average height of the seven tallest trees at age 16. Their analysis showed a highly significant negative correlation between dominant height and initial planting density.

Long-term field studies are subject to catastrophic events. In the 11th year of the trials (winter of 1994), a severe ice storm badly damaged several plots on the northernmost Piedmont site. Using stem quality assessment data collected after the storm, Amateis and Burkhart (1996) developed prediction equations for estimating the probability of five levels of stem bending and top breakage based on a proportional odds model.

At age 20, most of two blocks at the northernmost Piedmont site were attacked by southern pine beetles, and a decision was made to discontinue measurements on these blocks. Following abandonment, 34 sample trees from 10 spacing treatments were felled, and data were collected on whorl height aboveground, status of whorl (live, sound, decayed, or knot), and branch diameter. Dissection of whorls in the laboratory yielded information on knot size and shape and branch diameter growth. These data from the field and laboratory were used to construct models of branch diameter growth and knot formation along the boles of loblolly pine trees (Trincado and Burkhart 2008, 2009).

The southernmost Piedmont location was abandoned at year 20 because of a land sale and subsequent thinning operation. Thus, from age 21 to the end of the study, 7 of the original 12 blocks were still being measured: 6 in the Coastal Plain and 1 in the Piedmont.

Data from this study have also been used to evaluate the impact of rectangularity on growth and development of loblolly pine. Survival and the development of height, diameter, volume yield, and basal area were not affected by rectangularity out to a 3:1 ratio of between-row to within-row tree distance (Sharma et al. 2002a, 2002b). Bole condition and stem asymmetry were not affected by rectangularity. Although extreme rectangularity has significantly affected maximum branch diameter, the mean branch diameter has not been found to be large enough to degrade the butt log for the 12 × 4 rectangular spacing of this study (Amateis et al. 2004).

In recent years, the trials have yielded important information about height, dbh, and basal area growth relationships. Amateis et

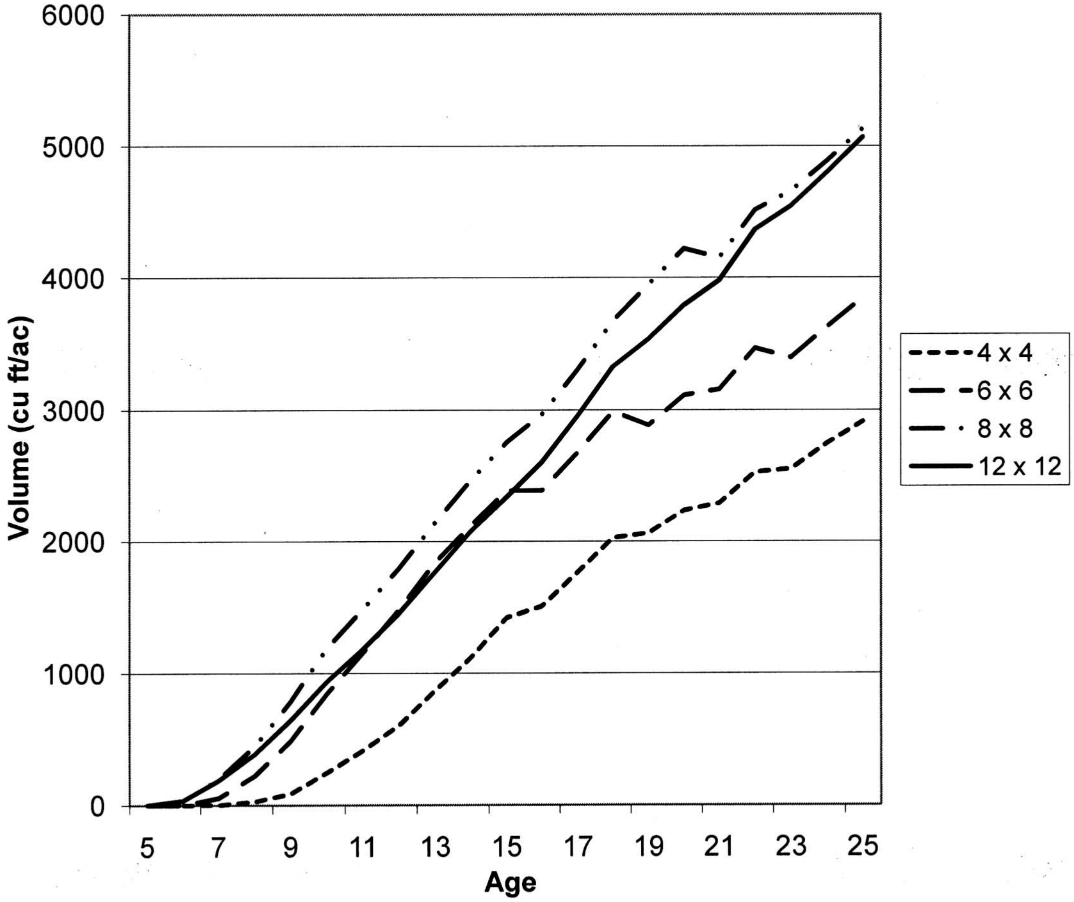

Figure 3. Cubic-foot pulpwood volume outside bark (5-in. dbh class and above to a 4-in. top diameter outside bark) for the 4 × 4-ft, 6 × 6-ft, 8 × 8-ft, and 12 × 12-ft square spacing treatments for ages 5 through 25 of the loblolly pine spacing trials.

al. (2009) found no correlation between row orientation, spacing treatment, and height and dbh growth at any age of plantation development. The mean height and dbh data presented in Table 2 suggest that both are affected by planting density. Work by Antón-Fernández et al. (in press, a) has quantified and modeled the relationship between height development and establishment density. Using the full range of data over the life of the study, they found that density begins to affect dominant height development by age 6 and continues to influence height development through age 25. This confirms the earlier work of MacFarlane et al. (2000) and suggests that site index determination can be affected by initial density. Additional work by Antón-Fernández et al. (in press, b) evaluated the effect of planting density on basal area development over the life of the study. Their work quantified the downturn in basal area observed for dense plantings and the asymptotic behavior seen in less dense plantings. A combined exponential and power function was used to model both developmental patterns.

These spacing trials, because of the wide range of initial densities and long-term measurements, have provided important new information on maximum size-density relationships and self-thinning. VanderSchaaf and Burkhart (2007) compared methods for estimating Reineke's maximum size-density boundary line slope using the spacing trial data. The data were also used (VanderSchaaf and Burkhart 2008) to construct regressions relating stages (density-independent, density-dependent) and phases (curved approach, linear, divergence within the self-thinning phase) of the maximum size-density relationship to planting spacing.

Clearly, results yielded by the trials over the years have met goals 1 and 2 by shedding light on a number of aspects of loblolly pine plantation growth and development. The purpose of this analysis is to consider goal 3 of the study: How does planting density affect yield for particular product definitions?

Methods

Because heights were measured biennially after age 10, linear interpolation was used to estimate total height for the years lacking an observed height. At age 25, the crown class (dominant or codominant, intermediate or suppressed) of each tree was recorded, and total height was measured. Average height of the dominant and codominant trees was computed to obtain an exhibited site index for each treatment plot (Table 2).

Diameter and heights for each live tree were used to estimate total outside bark volume of the main stem using the individual tree total volume equation of Tasissa et al. (1997). The Tasissa et al. (1997) merchantable volume equations were used to compute three estimates of merchantable yield. For trees in the 5-in. dbh class (dbh at least 4.6 in.) and above, an estimate of merchantable pulpwood volume to a 4-in. top diameter outside bark was computed. Similarly, trees in the 8-in. dbh class and above to a 6-in. top diameter outside bark were used to compute an estimate of chip-and-saw

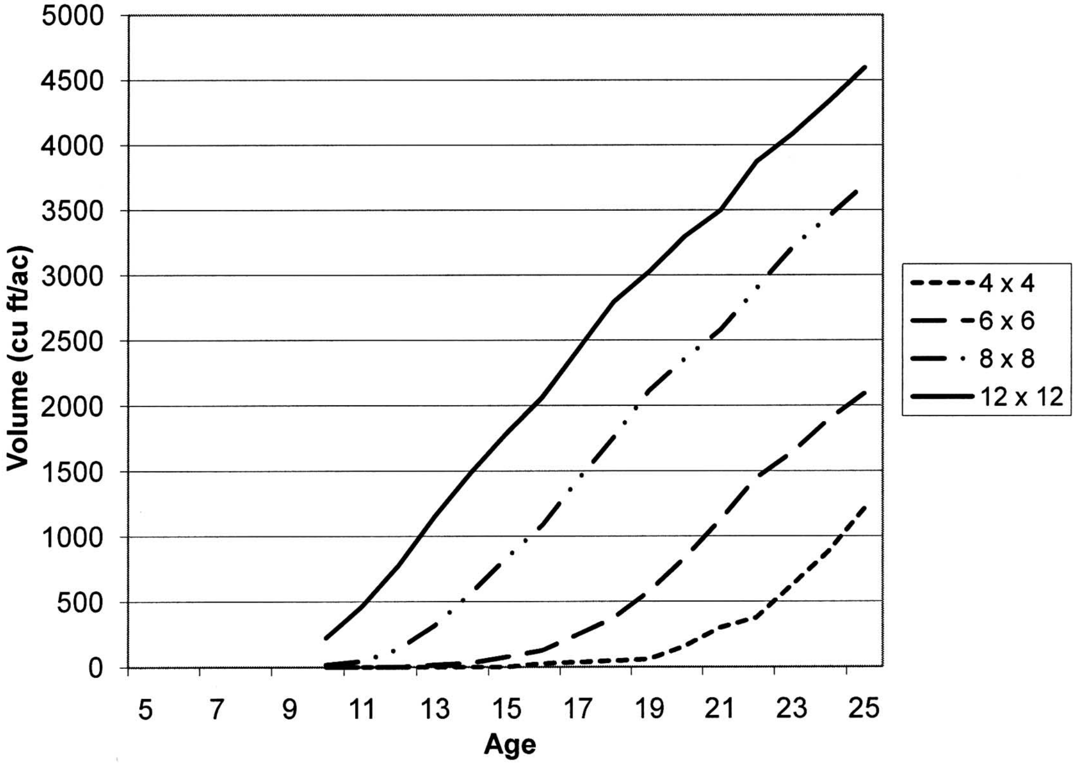

Figure 4. Cubic-foot chip-and-saw volume outside bark (8-in. dbh class and above to a 6-in. top diameter outside bark) for the 4 × 4-ft, 6 × 6-ft, 8 × 8-ft, and 12 × 12-ft square spacing treatments for ages 10–25 of the loblolly pine spacing trials.

volume, and trees in the 11-in. dbh class and above were used to compute an estimate of sawtimber volume to an 8-in. top diameter outside bark. Per-acre summaries of total and merchantable volumes were computed for each treatment plot and averaged across all surviving blocks and locations of the study at each age (Table 2 and Figures 2–5). Recognizing that specific products, merchantability standards, and product metrics, such as volume or weight, will vary with local markets, it should be possible to relate the cubic-foot volume per acre results presented here to other standards and product specifications.

Results and Discussion

Figure 2 summarizes total volume outside bark yield production for the square spacing treatments over the life of the study. Plots established at high densities and close spacings outproduced plots established at low densities and wide spacings through the early years of the study. The 4 × 4-ft treatment plots produced more total volume yield through age 13 than any other treatment plot. By age 15, however, increased mortality in the 4 × 4-ft plots reduced yield production below plots established at lower densities and wider spacings. Thus, management strategies geared toward total biomass production suggest that high initial establishment densities and short rotations will be optimal.

Figure 3 summarizes pulpwood production for the square spacing treatments. No treatment produced more pulpwood volume than the 8 × 8-ft spacing treatment. Where pulpwood production is the management objective, plantation establishment densities in the neighborhood of 680 trees/ac should be optimal for rotations of 25 years or less and site qualities similar to those included in these trials. With regard to pulpwood production, results from this study are consistent with those of Harms and Lloyd (1981).

Figures 4 and 5 present the development of chip-and-saw and sawtimber production, respectively, for the square spacing treatments. Management strategies that are optimal for solidwood products will include wider spacings and fewer trees planted. In this study, the 8 × 12-ft and 12 × 12-ft spacing treatments produced more chip-and-saw than other treatments for all ages. The 12 × 12-ft (302 trees/ac) planting density produced more sawtimber across all ages, by a wide margin, than any other spacing treatment. By age 25, the 12 × 12-ft spacing had almost twice as much sawtimber as the 8 × 12-ft spacing (454 trees/ac planted) (Table 2). When sawtimber production is the goal and thinning is not part of an overall stand management plan, 300 trees/ac planted does not appear to underuse the site.

An important finding from this study is that rectangularity was not an important factor affecting yield production. By age 25, differences between yields of the 4 × 12-ft spacing treatments and the 6 × 8-ft spacing treatments (48 ft^2 of growing space per tree) were not statistically significant. This suggests that where site preparation and planting costs can be reduced for a given number of trees planted by establishing fewer rows, spacings with increased between-row planting distances and decreased within-row distances can be implemented.

In summary, the major conclusions from this study are as follows:

1. The particular planting density selected has a far greater effect on yield and the products obtained at harvest than the degree of rectangularity. In other words, the shape of the growing space per tree is not nearly as important as the amount of growing space per tree.

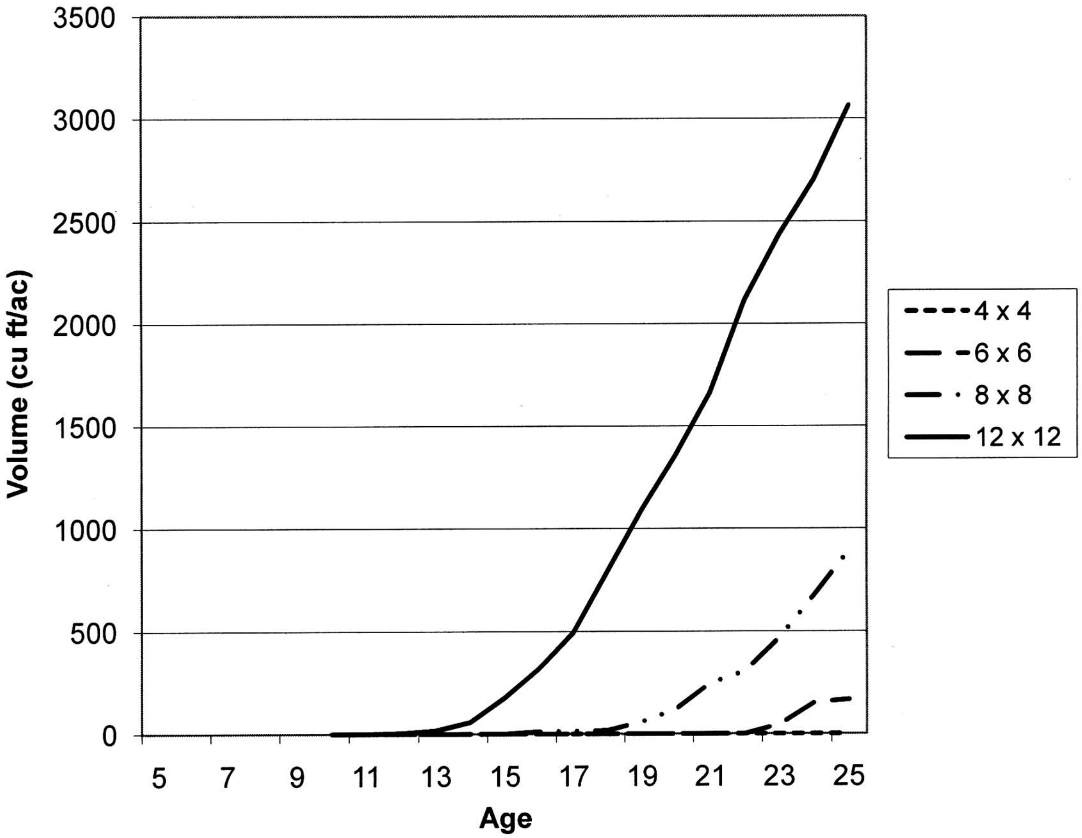

Figure 5. Cubic-foot sawtimber volume outside bark (11-in. dbh class and above to an 8-in. top diameter outside bark) for the 4 × 4-ft, 6 × 6-ft, 8 × 8-ft, and 12ft x 12 ft square spacing treatments for ages 10–25 of the loblolly pine spacing trials.

2. In the absence of thinning, there is an inverse relationship between planting density and size of products realized at harvest. Product objectives at harvest that include large sawtimber trees will require fewer trees per acre planted. Assuming no thinning, a planting regime of 300 trees/ac appears reasonable for growing sawtimber over a 25-year rotation on sites similar to those included in this study. Conversely, total biomass production goals can best be met by establishing high-density plantations managed on short rotations.
3. Management objectives focused on realizing pulpwood yields can be achieved by planting about 680 trees/ac on lands exhibiting site quality similar to that of these plantings.

Considered together, the results of this study suggest that no single planting density will be optimal for all management objectives. Rather, managers will need to consider product objectives desired at final harvest and whether opportunities for thinning and other silvicultural interventions will be present during midrotation when selecting an initial planting density.

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