PMRC SAGS CULTURE / DENSITY STUDY:

AGE 8 ANALYSIS

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SUMMARY

The SAGS Culture / Density study was established in 1997/98 to examine the effects of intensive silviculture and current operational practices on the growth and yield of loblolly pine across a wide range of densities. The study was stratified across seven broad soil classes, four in the Piedmont and three in the Upper Coastal Plain. Twenty-four installations were established in the Piedmont and upper coastal plain regions of Georgia and Alabama. Both the operational and intensive treatments included a chemical site preparation treatment. Any tillage treatments included in site preparation were carried out on all treatment plots. At planting, 500 lbs/ac of 10-10-10 fertilizer were applied on all plots. The intensive culture plots also received 600 lbs/ac of 10-10-10 after the second growing season plus micronutrients and 117 lbs/ac of NH_4NO_3. At the beginning of the 4th growing season they received another 117 lbs/ac of NH_4NO_3, and at the beginning of the 6th growing season they received 300 lbs/ac of NH_4NO_3. At the beginning of the 8th growing season, operational and intensive plots received an additional 200 lbs/ac elemental N and 25 lbs/ac elemental P. The intensive cultural treatment plots received additional herbicide treatments to keep them as free of competing vegetation as possible throughout their rotation.

Within both the intensive and operational treatments, six loblolly pine subplots with densities of 300, 600, 900, 1200, 1500 and 1800 trees per acre (tpa) were randomly located and established. The arrangement of cultural treatments and planting densities results in a split plot design. The main plots are cultural treatments and densities are the sub-subplots. The installations are considered as a random sample of all possible locations so the installation (replication) factor is considered random. Since the other factors are fixed, this results in a "mixed model" and the data were analyzed as such. Dormant-season tree measurements were collected at ages 2, 4, 6 and 8 years. The analysis was carried out for average DBH, average height, average dominant height, percent survival, percent cronartium infection, per-acre basal area, total per-acre outside bark total volume and green weight, stand density index, relative spacing, crown length and crown ratio.

At age eight, the management intensity factor and the density factor had significant effects on average DBH. There was also a significant density x management interaction for average DBH. There was a larger gain in average DBH for 300 trees per acre for intensive management than for the higher initial densities. Average DBH's by treatment ranged from 3.8" for the operational, 1800 tpa plots to 7.8" on the intensively-managed, 300 tpa plots.

Both the management intensity and initial density factors had significant effects on pine average height, but there was no significant interaction. There was a gain of 4-5 ft as a result of intensive

management as compared to operational management and there was a trend toward shorter average heights as density increased above 900 trees per acre for both operational and intensively-managed plots. Average top height, defined as the average height of trees with above-average DBH values, followed the same trends as average height of all trees. Differences due to management were exhibited from age two while density-related effects on height have become apparent since age six.

Only initial density was a significant factor for average percent survival. There was a trend towards lower percent survival with increasing initial density, especially for the intensively-managed plots. Survival was excellent overall with the lowest percent survival of 86.5% on the intensively-managed 1800 tpa plots.

Cronartium infection rates were generally low with a maximum of 7.4%. Initial density significantly affected cronartium infection levels and there was a significant density x management interaction. Intensively-managed plots with an initial density of 300 trees per acre had the highest infection rate by 3.4% over the next-highest treatment. The next greatest difference in average infection rates between treatments was 0.7%.

Management intensity and initial density were significant factors for basal area, total volume per acre and total green weight per acre. Basal area per acre increased as initial density increased. Intensively-managed plots had 25-31 ft^2/ac more basal area than operationally-managed plots. Total stem volume outside bark also increased with increasing density and intensively-managed plots had 494-714 ft^3/ac more wood at age eight than operationally-managed plots. Total stem green weight outside bark increased with increasing density with intensively-managed plots having 13-19 tons/ac more wood at age eight than operationally-managed plots on average.

Initial density and management were significant factors for the average stand density index (SDI) value. The maximum value for loblolly pine is considered to be 450. As density increased the SDI increased for both intensive and operationally-managed plots. The intensively-managed plots averaged 53 units higher than the operationally-managed plots. The intensively-managed plots had values of about 360-410 for 1200 or more trees per acre.

Density, management intensity, and the interaction of management intensity and density were significant variables for relative spacing (RS). Relative spacing, the average distance between trees assuming square spacing divided by the dominant height, normally decreases as stands develop and for loblolly pine approaches a lower asymptote of about 0.12. As density increased the relative spacing decreased for both operational and intensive management with operational

RS always being larger for a given density. The interaction came from a decreasing difference between RS values for the two management intensities as the density increased.

Management intensity, initial density and their interaction significantly impacted average crown length. Crown length decreased with increasing planting density. The intensively-managed plots had consistently higher crown lengths than operational plots but the management effect varied by initial density. Crown length development has slowed since age four and crown length has decreased for operational treatments of 1500 tpa and above and for intensive treatments of 900 tpa and above.

Crown ratio values for all treatments were found to be within the acceptable range for vigorously-growing trees (>40%). Management intensity, initial density and their interaction significantly affected crown ratio. Crown ratio steadily declined with initial density from a high of .72 at 300 tpa to a low of .45 at 1800 tpa. The operational treatments had consistently higher crown ratios than the intensively-managed plots but trees on the intensively-managed plots were taller, overall, and had longer crowns.

Stand development was accelerated for both of the tested management intensities compared to that for typical operational plantations established during the last 15-20 years. For intensively-managed plots, the average basal area across all installations for 1200 trees per acre and higher was about 155 ft^2/ac at age eight. By comparison, the basal area for the operational treatment with 600 trees per acre was 90 ft^2/ac, a growth rate over 10 ft^2/ac/yr and still considered exceptional. Though these stands are only eight years old they are quickly getting to a level of stand development where they can provide answers to planting density x management intensity questions that are key to improved plantation management.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Industrial forest landowners in the southeastern U.S. have experienced increasing pressure to maximize volume production from loblolly pine plantations. As the demand for forest products continues to increase, the amount of land on which pine plantation management is feasible or practical continues to decrease. These pressures have created significant interest in genetic improvement, control of competing vegetation and forest nutrition. Many studies carried out by the PMRC and other researchers have reported significant gains in yield due to tree improvement and more intensive management practices. When contemplating the regeneration of a loblolly pine plantation, forest managers in the southeastern U.S. still have unanswered questions regarding the relationships between management practices and establishment densities across a range of soil types. To address this issue, the PMRC established the Coastal Plain Culture / Density Study in 1995/1996 followed by the SAGS Culture / Density Study in 1997/98. The objectives of these studies are to:

- Quantify and contrast the effects of intensive silviculture and current operational practices on the growth and yield of loblolly pine plantations across a wide range of densities.
- Investigate potential interactions between cultural intensity and stand density across broad soil categories, particularly in the areas of survival, merchantable green and dry weight production and product class distributions.
- Describe and compare the development of stand leaf area index (LAI) produced by the various combinations of cultural intensity and stand density.

This report covers the eight-year results from the SAGS Culture / Density Study. The analysis reported here was limited to culture and density affects without consideration of soil-site impacts. This will be addressed in future reports. Leaf area has been evaluated on selected locations and reported on by Will, *et.al*, 2005.

2 METHODS

Twenty-four installations were established in the Piedmont and Upper Coastal Plain regions of Georgia and Alabama. The study was stratified over seven broad soil classes, four in the Piedmont and three in the Upper Coastal Plain. Tables 1 and 2 show the soil characteristics used to classify the soils.

Table 1. Soil groups used in the SAGS Culture / Density Study plots in the Piedmont.

Subsoil Parent Material	Topsoil Depth
Montmorillonite / Mixed Clay	< 3 inches
Montmorillonite / Mixed Clay	> 3 inches
Kaolinite	< 3 inches
Kaolinite	> 3 inches

Table 2. Soil groups used in the SAGS Culture / Density Study plots in the Upper Coastal Plain.

Drainage Class	Argillic Horizon Depth
Moderately well to well drained	< 20 inches
Moderately well to well drained	20-40 inches
Moderately well to well drained	> 40 inches

Site preparation and subsequent silvicultural treatments represent two levels of management intensity; operational and intensive culture. The treatments carried out for each management level are summarized in Table 3.

Table 3. Silvicultural treatments for the SAGS Culture / Density study

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Treatment	Operational	Intensive
Chemical Site Preparation	High-rate broadcast treatment in late summer/fall	High-rate broadcast treatment in late summer/fall
Mechanical Site Preparation	Optional, Cooperator select, applied to all plots	Optional, Cooperator select, applied to all plots
Fertilization	At Planting: 500 lbs/ac 10-10-10 Before year 8: 200 lbs/ac N + 25 lbs/ac P	At Planting: 500 lbs/ac 10-10-10 After year 2: 600 lbs/ac 10-10-10 + 117 lbs/ac NH_4NO_3 + micronutrients Before year 4: 117 lbs/ac NH_4NO_3 Before year 6: 300 lbs/ac NH_4NO_3 Before year 8: 200 lbs/ac N + 25 lbs/ac P
Weed Control	Year 1: 4 oz/ac Oust banded + directed spraying for hardwood control	Year 1: 4 oz/ac Oust broadcast + directed spraying for complete competing vegetation control After year 1: 12 oz/ac Arsenal broadcast To Date: Repeated directed spraying for complete competing vegetation control

Within each site preparation treatment, six subplots with densities of 300, 600, 900, 1200, 1500 and 1800 trees per acre (tpa) were planted. To ensure adequate first-year survival, trees were double-planted and reduced to a single surviving seedling after the first growing season. Table 4 shows the spacings and plot sizes for the density subplots.

Table 4. Spacing and plot sizes for the density subplots.

Density (tpa)	Spacing (ft. x ft.)	Trees per meas. Plot	Meas. plot size (ac)	Gross plot size (ac)
1800	6 x 4	184	0.10	0.31
1500	6 x 4.8	160	0.11	0.32
1200	6 x 6	120	0.10	0.30
900	8 x 6	96	0.11	0.31
600	8 x 9	80	0.13	0.37
300	12 x 12	80	0.26	0.56

The arrangement of cultural treatments and planting densities results in a split plot design. The main plots are cultural treatments and densities are subplots. Since the replications or installations in this case, can be considered as a random sample of all possible locations, the replication factor must be considered as random. This results in a mixed model. In order to make proper inferences across all sites, the presence of the random factor must be considered (Parrish and Ware, 1989; Littell *et.al.*, 1991). All factors containing installation were considered random and were listed in the RANDOM statement in SAS PROC MIXED (Littell *et.al.*, 1996).

Dormant-season tree measurements were collected at ages 2, 4, 6 and 8 years. After the fourth growing season, diameters of all trees (DBH) were measured. Total height (ft) and height to live crown were measured on every other tree. Total heights of unmeasured trees were estimated using regression. Each tree was also inspected for cronartium infection and tip moth damage. Individual tree, outside bark cubic foot volumes and green weights with bark were calculated using the following equations from Pienaar, *et. al.,* 1987:

$$TVOB = 0.00401246\, DBH^{1.829011}\, HT^{0.969142}$$

$$GWWB = 0.110069\, DBH^{1.935455}\, HT^{1.080621}$$

where TVOB =total stem volume outside bark (o.b.) in ft^3,
GWWB = total stem green weight (o.b.) in lbs,
DBH = diameter at breast height (in), and
HT = total tree height (ft).

Survival percentages were computed using the observed number of trees per acre at age eight and the specified planting density that was imposed after the first growing season.

Stand density index was calculated for each plot using the following equation:

$SDI = N*(10/Dq)^{-1.6}$

where SDI = stand density index,

N = trees per acre surviving at the SDI age, and

Dq = quadratic mean DBH.

Relative spacing was calculated for each plot using the following equation:

RS = SQRT[43560/N]/Hd

where SQRT = square root

N = trees per acre surviving at RS age,

Hd = average height of dominant trees.

Analysis of variance as described above was carried out for average DBH, average height, average dominant height, percent survival, percent cronartium infection, per-acre basal area, per-acre total volume, per-acre green weight, stand density index, relative spacing and crown ratio. All tests of significance were made at the $\alpha = 0.05$ significance level. Loblolly pine mean tree and stand characteristics by management intensity and initial density at age eight are presented in Table 5.

Table 5. Loblolly pine means by management intensity and initial density at age eight.

Management	Planting Density	Avg. Dbh (in)	Avg. Height (ft)	Avg. Dom. Height (ft)	% Surv	% Cron	Basal Area/ac (ft^2/ac)	Total Vol/ac (ft^3/ac)	Total Wt/ac (tons/ac)
Intensive	300	7.8	36.2	37.6	92.9	7.4	92.5	1569	40.2
	600	6.2	36.8	38.4	92.9	4.2	121.2	2184	54.9
	900	5.5	36.2	38.0	91.7	3.8	137.4	2487	61.5
	1200	5.0	35.7	37.6	90.2	2.9	148.8	2705	66.1
	1500	4.6	34.6	36.7	89.1	3.0	155.8	2797	67.6
	1800	4.3	34.2	36.3	86.5	2.7	159.5	2877	69.1
Operational	300	6.5	32.5	34.1	94.1	4.0	67.2	1075	26.8
	600	5.4	32.2	34.0	92.1	4.4	90.0	1475	36.1
	900	4.8	32.7	34.4	94.2	3.1	110.1	1862	45.0
	1200	4.4	31.5	33.6	91.3	3.1	119.7	1991	47.6
	1500	4.0	30.8	32.9	92.7	2.6	126.7	2107	49.8
	1800	3.8	30.4	32.6	91.5	3.2	133.3	2211	51.9

3 LOBLOLLY PINE RESULTS AT AGE EIGHT

3.1 Average DBH

Table 6 shows the results of the analysis of variance for average DBH for loblolly pine. The management intensity factor was significant as was density and there was also a significant management x density interaction. Average DBH by management intensity and initial density is shown in Figure 1.

Table 6. Analysis of variance results for loblolly pine average DBH at age eight.

Source	Type III F	Pr > F
Management	141.84	<0.0001*
Density	832.51	<0.0001*
Management x Density	12.05	<0.0001*

*Significant at α = 0.05.

There was a consistent trend toward lower average DBH values as density increased for both intensive and operational management. At all densities, the intensively managed plots had larger average DBH's than the operational plots. This interaction was probably caused by the increased level of stand development on the intensively managed plots resulting in a larger decrease in average DBH as density increased. While the same general trend is present on the operational plots, the differences in average DBH across the range of densities were much smaller. Also, the level of development means that the operational plots shaded out competition at an early age at the higher densities and therefore grew more like the intensively-managed plots. At low densities, this did not occur and the competition effect is shown in lower DBH values for the operational plots. Figure 2 shows DBH development over time for selected treatments. It is interesting to note the vastly different curve shapes resulting from different management intensity and initial density.

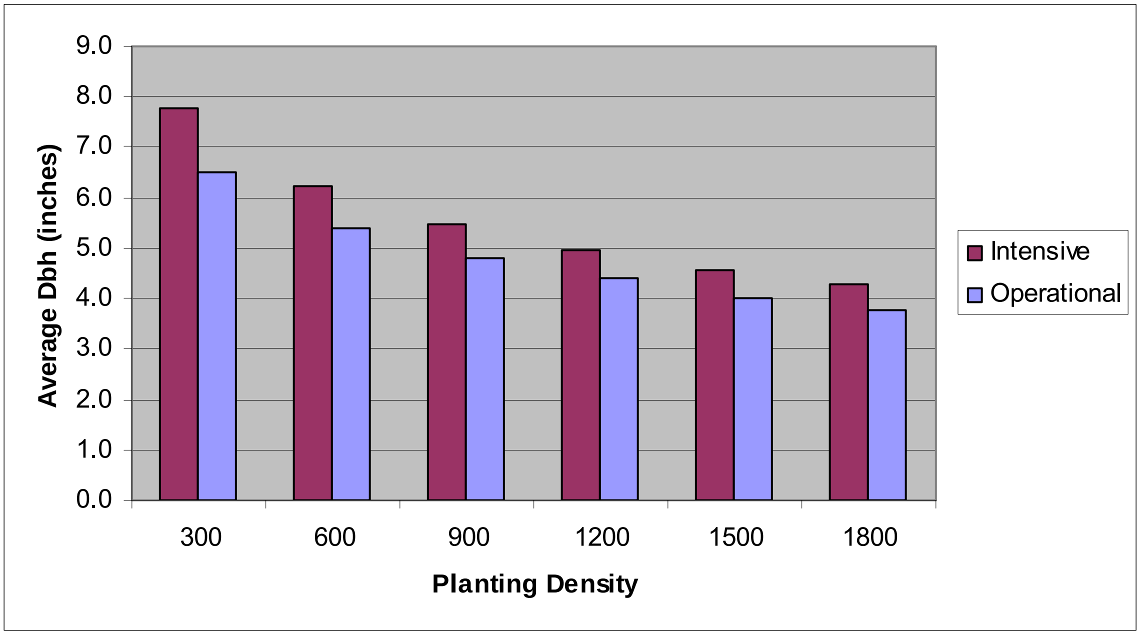

Figure 1. Average DBH by planting density and management intensity for loblolly pine at age eight.

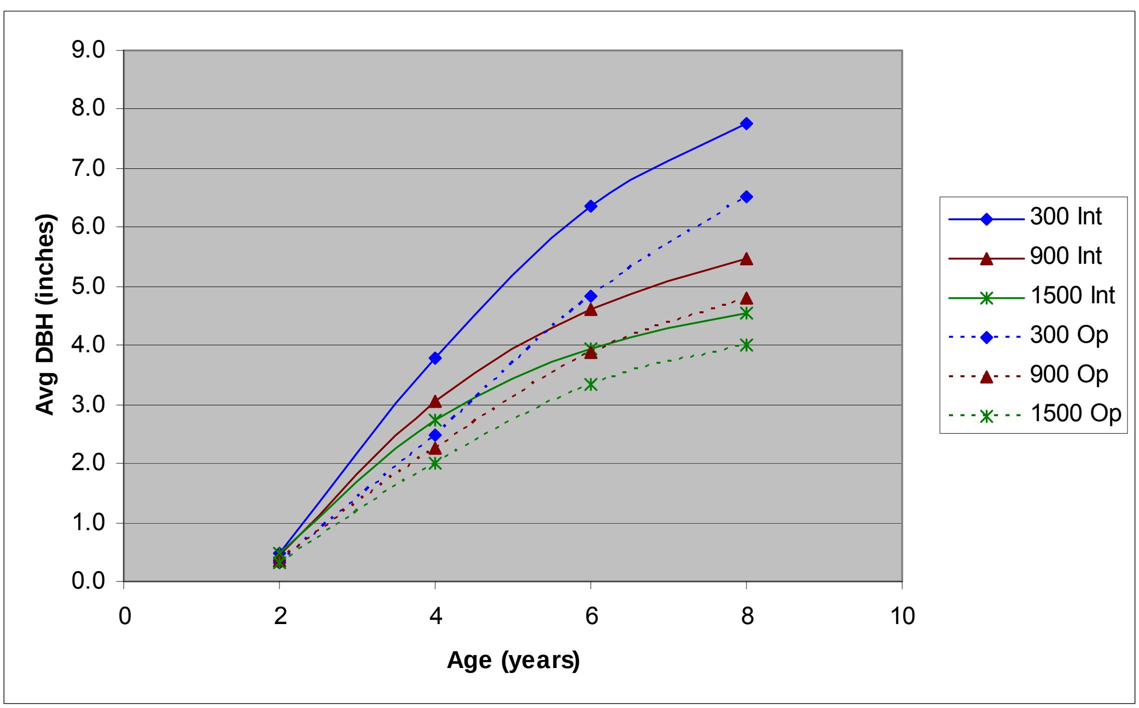

Figure 2. Average DBH growth by planting density and management intensity for selected loblolly pine treatments.

3.2 Average Height

Results of the analysis of variance for loblolly pine average height are displayed in Table 7. The management intensity factor was significant at the α = 0.05 level with the intensive culture treatment heights averaging 3.5 to 4.6 feet taller across the different densities. The density factor was also significant, but there was no management intensity x density interaction. The density was significant due to consistently lower average heights at higher densities, but from a practical point of view the differences were only to 2-3 feet. Average height (Figure 3) and average "top height" (Figure 4) show similar trends by management intensity and initial density. The analysis of variance indicated that management intensity and density significantly affected mean "top height" at the 5% level of significance. Differences in average height due to management intensity were exhibited from age two, but differences due to density have only appeared from age six (Figure 5).

Table 7. Analysis of variance results for loblolly pine average height at age eight.

Source	Type III F	Pr > F
Management	55.91	<0.0001*
Density	20.33	<0.0001*
Management x Density	0.85	0.5177

*Significant at α = 0.05.

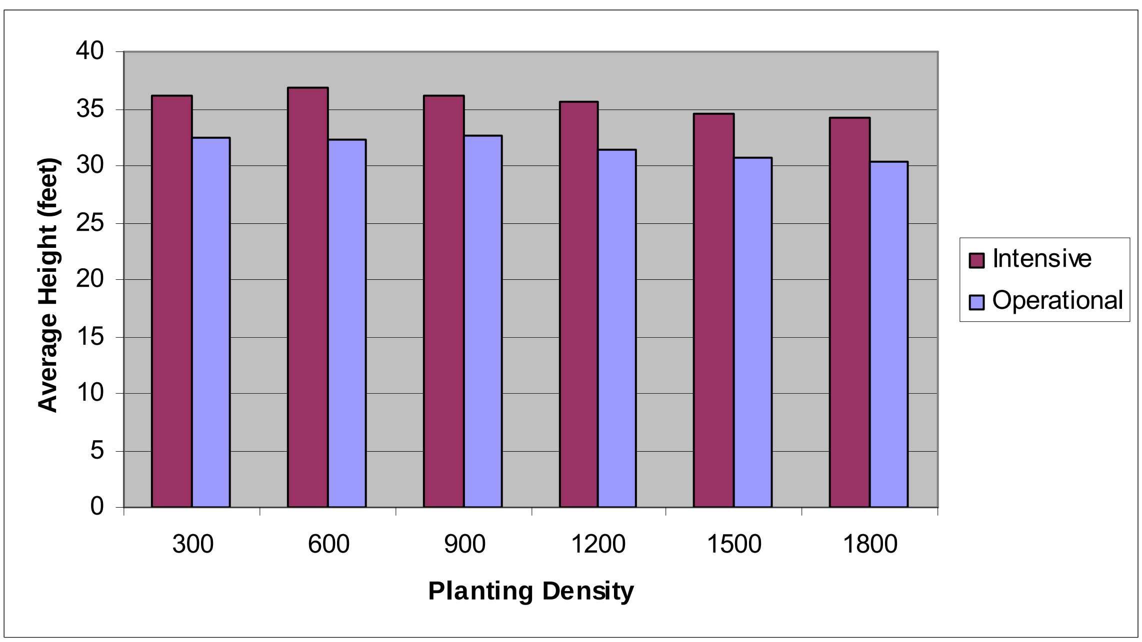

Figure 3. Average height by planting density and management intensity for loblolly pine at age eight.

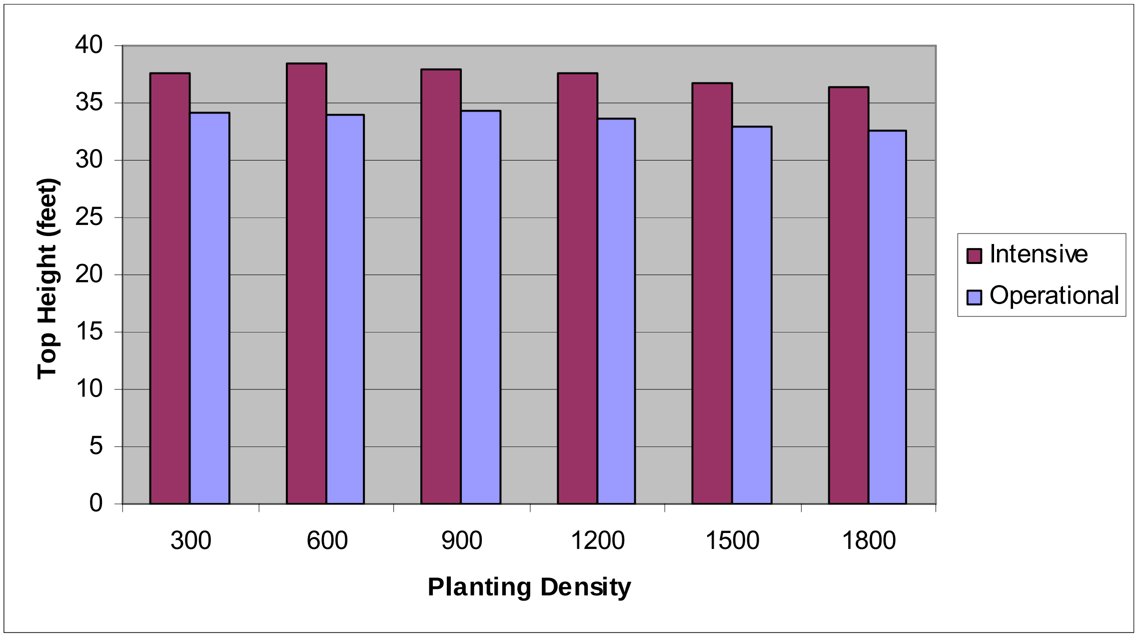

Figure 4. Average top height by planting density and management intensity for loblolly pine at age eight.

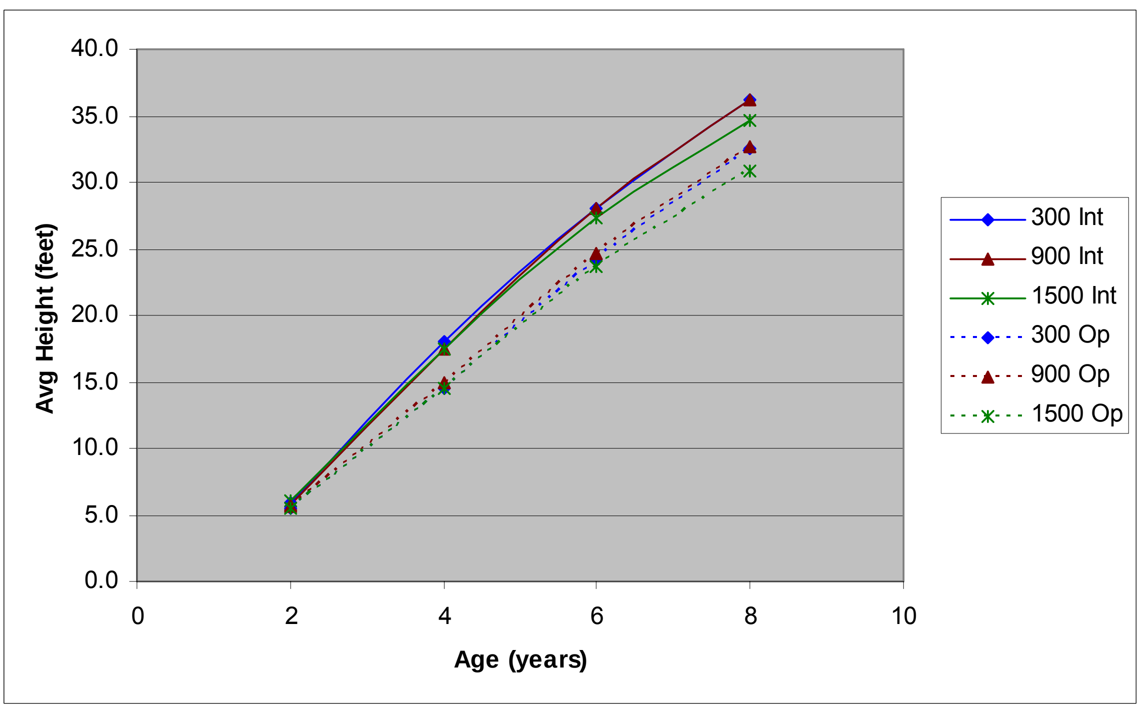

Figure 5. Average height growth by planting density and management intensity for selected loblolly pine treatments.

3.3 Percent Survival

The lowest average percent survival, observed on the intensively-managed 1800 trees per acre density, was 86.5%. The density factor had a statistically-significant effect on survival (Table 8). Planting densities of 300-900 tpa averaged 93% survival while planting densities of 1200-1800 tpa averaged 90.2% survival (Figure 6). Survival trends for selected treatments indicate that density-related mortality has begun to take effect on the higher-density plots (Figure 7).

Table 8. Analysis of variance results for loblolly pine average percent survival at age eight.

Source	Type III F	Pr > F
Management	2.50	0.1282
Density	3.40	0.0056*
Management x Density	1.25	0.2889

*Significant at α = 0.05.

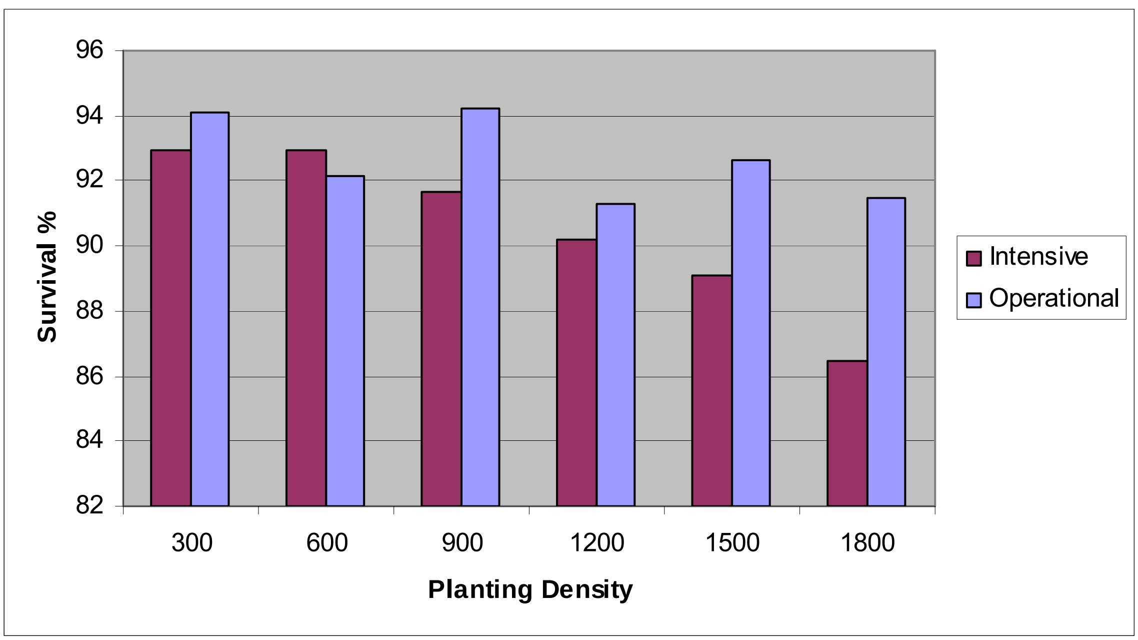

Figure 6. Percent survival by planting density and management intensity for loblolly pine at age eight.

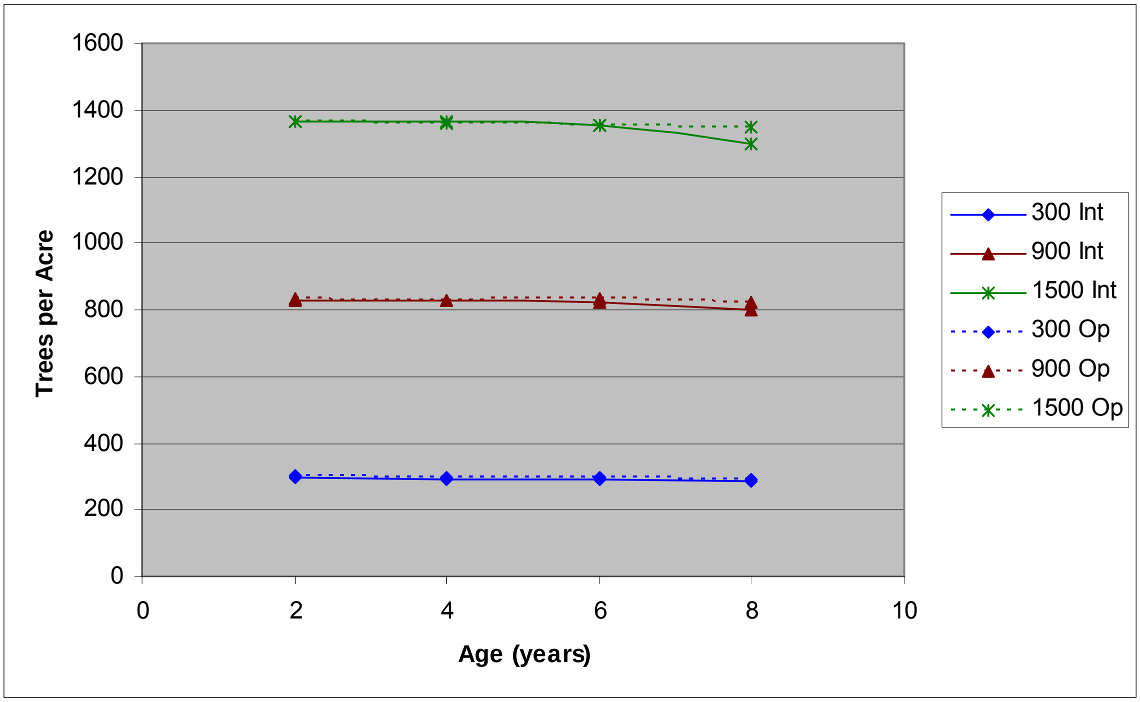

Figure 7. Average survival by planting density and management intensity for selected loblolly pine treatments.

3.4 Percent Cronartium Infection

Average cronartium infection rates were very low, ranging from approximately 2.6 to 7.4% for all densities and management regimes (Figure 8). The effect of management intensity was not significant but density and the management x density interaction significantly affected the cronartium infection rate (Table 9). There was a clear tendency for infection rate to decrease as density increased. The intensive management treatment at an initial density of 300 trees/acre had the highest average infection rate and the 300 density also had the largest difference between intensive and operational management. As indicated in previous studies of loblolly pine, treatments that tend to accelerate height and diameter growth also tend to increase the cronartium infection rate (Zutter *et al.,* 1987; Shiver and Harrison, 2000).

Table 9. Analysis of variance results for loblolly pine average percent cronartium infection at age eight.

Source	Type III F	Pr > F
Management	2.25	0.1479
Density	10.68	<0.0001*
Management x Density	4.60	0.0005*

*Significant at α = 0.05.

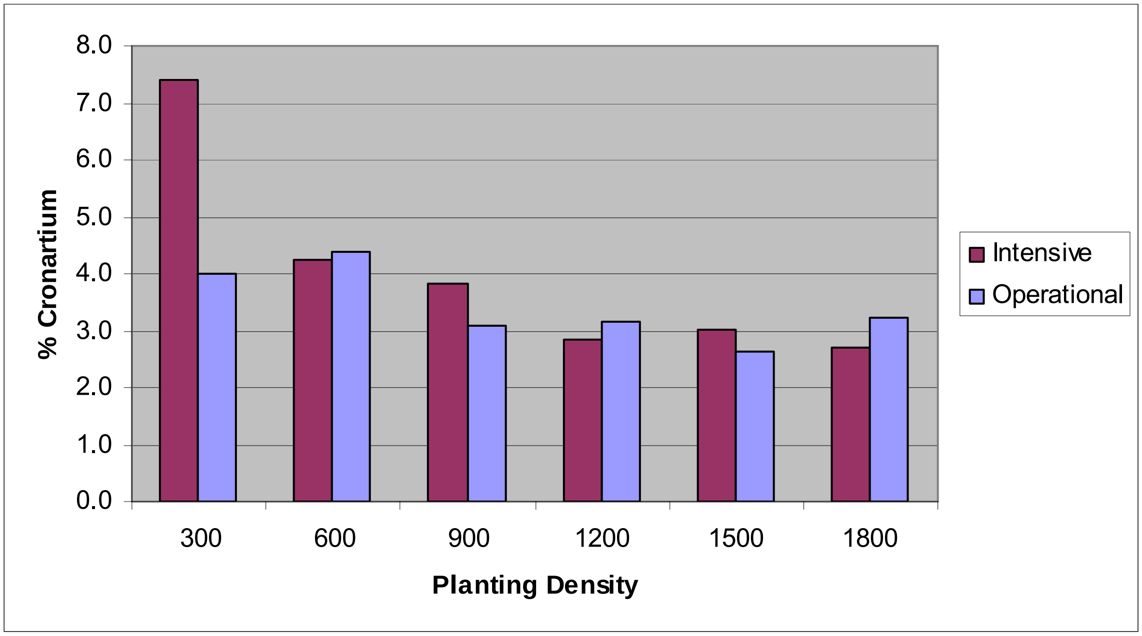

Figure 8. Average percent cronartium infection by planting density and management intensity for loblolly pine at age eight.

3.5 Per-Acre Basal Area

Management intensity and density were significant factors for per-acre basal area (Table 10). Basal area increased with increasing density and the gain for intensive management compared to operational management was very consistent across densities (Figure 9). The densities of 1200 to 1800 trees per acre had 149 to 160 ft^2/ac basal area on the intensively-managed plots. Gains for intensive management above operational averaged about 28 ft^2/ac. Based on observed basal area growth over time for selected treatments, it appears that all but the lowest densities have begun to slow down in basal area growth (Figure 10).

Table 10. Analysis of variance results for loblolly pine average per-acre basal area at age eight.

Source	Type III F	Pr > F
Management	190.25	<0.0001*
Density	295.53	<0.0001*
Management x Density	0.56	0.7330

*Significant at $\alpha = 0.05$.

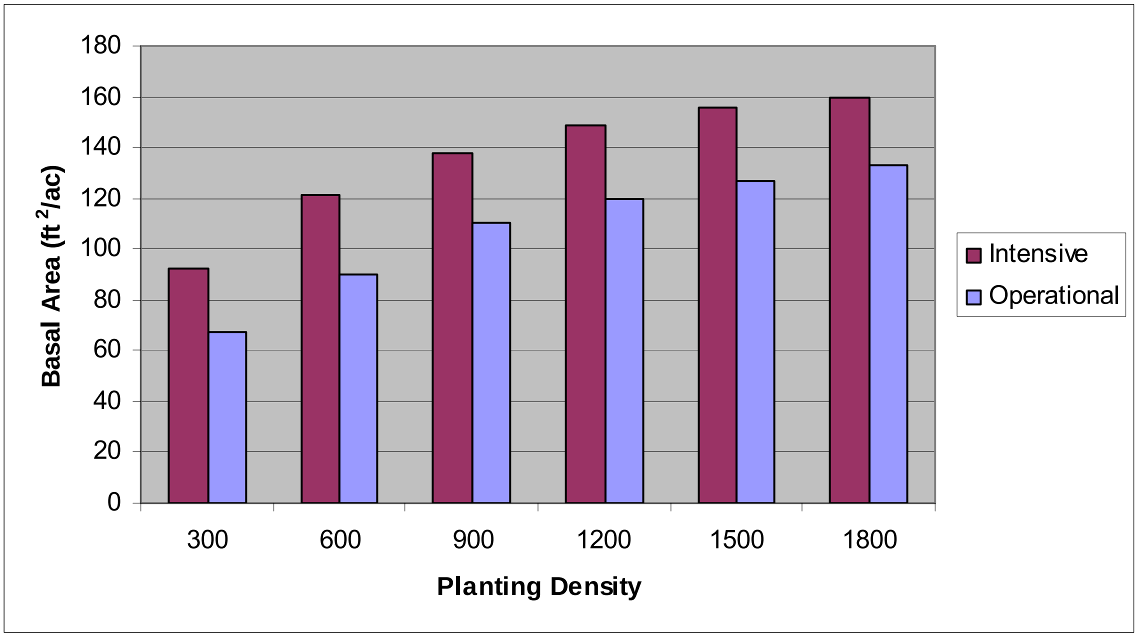

Figure 9. Average per-acre basal area by planting density and management intensity for loblolly pine at age eight.

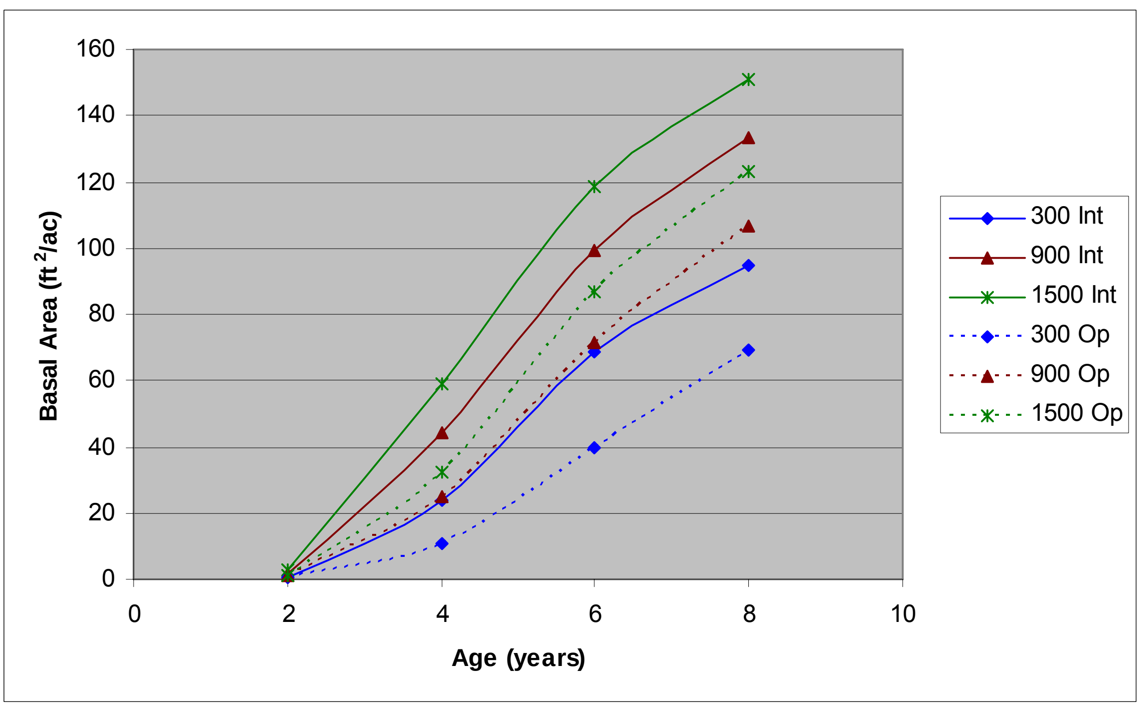

Figure 10. Average per-acre basal area growth by planting density and management intensity for selected loblolly pine treatments.

3.6 Per-Acre O.B. Volume

The results of the analysis of variance for per-acre total stem volume (Table 11) showed nearly identical trends as seen for per-acre basal area where management and density significantly affected per-acre volume. Total volume increased with increasing planting density (Figure 11). The intensive management treatments resulted in an average per-acre total volume of 494 to 714 ft^3/ac more than that of the operational treatments. Average volumes on the intensively managed plots on initial densities of 1200 to 1800 averaged 2700 to 2880 ft^3/ac. Using a conversion factor of 80 ft^3/cord, this translates to approximately 4.4 cords/ac/yr. Despite increases in mortality at higher densities, total volume continued to increase linearly through age eight for the treatments examined (Figure 12).

Table 11. Analysis of variance results for loblolly pine average per-acre, total volume at age eight.

Source	Type III F	Pr > F
Management	134.54	<0.0001*
Density	198.85	<0.0001*
Management x Density	1.60	0.1602

*Significant at α = 0.05.

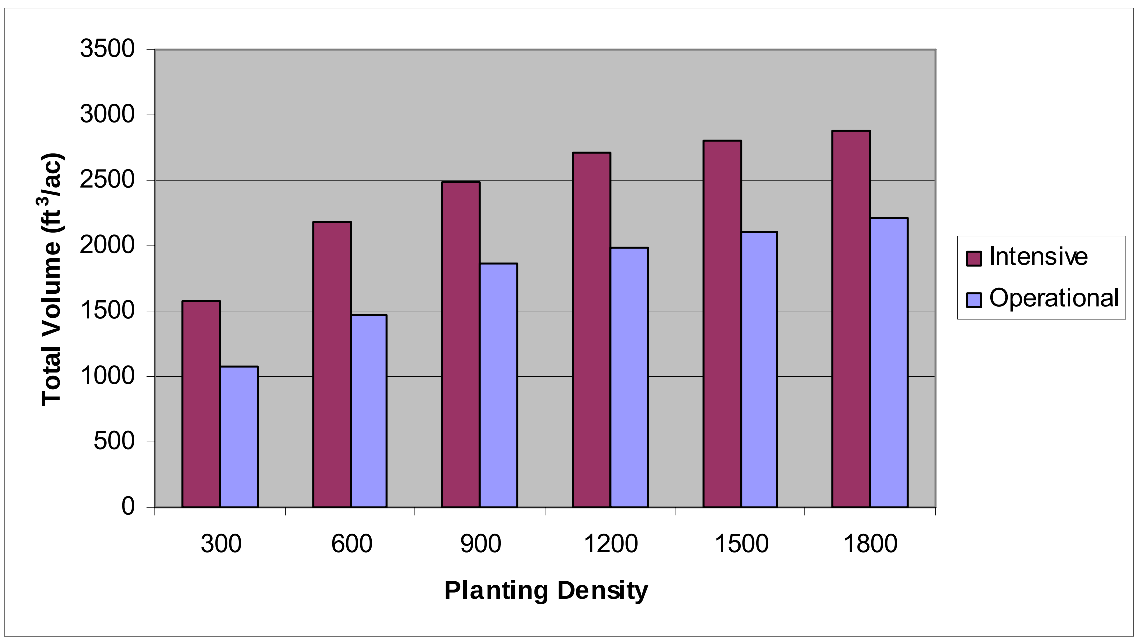

Figure 11. Average per-acre o.b. volume by planting density and management intensity for loblolly pine at age eight.

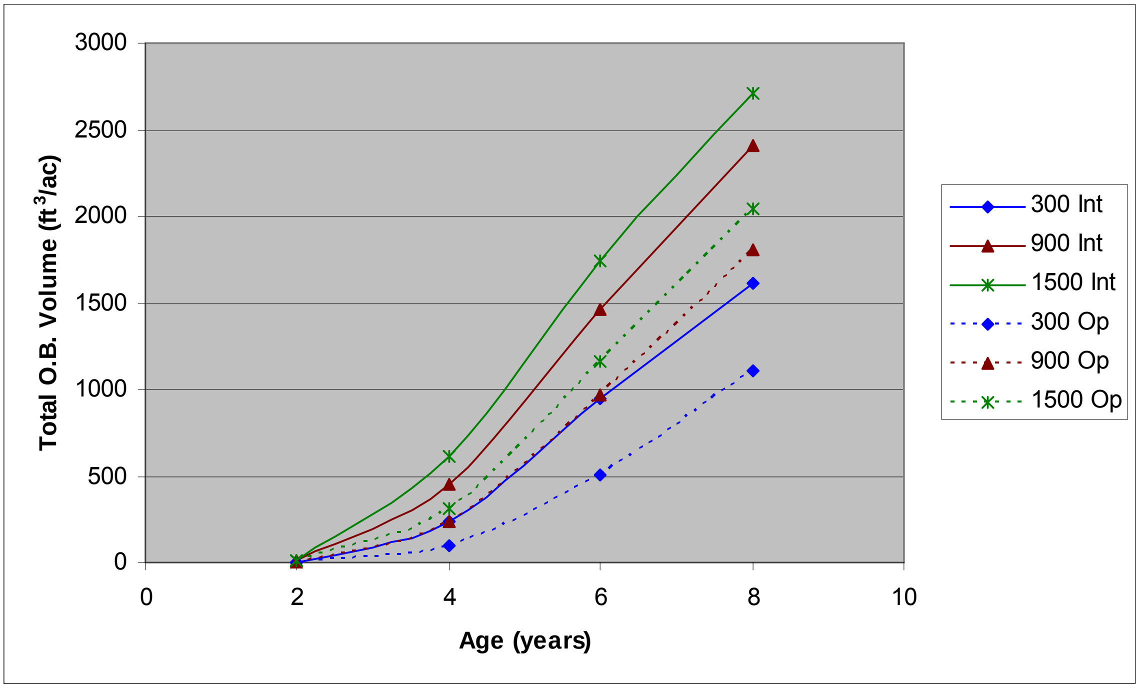

Figure 12. Average per-acre total volume growth by planting density and management intensity for selected loblolly pine treatments.

3.7 Per-Acre O.B. Green Weight

The results of the analysis of variance for per-acre total green weight (Table 12) exhibited nearly identical trends as seen for per-acre total volume and basal area. Management and density significantly affected per-acre green weight. Total green weight per acre increased with increasing density for both operational and intensive management (Figure 13). The gain from intensive management over operational management averaged 17 tons/ac over all initial densities. The 1200 to 1800 intensive management plots averaged 66-69 tons/ac at age eight (8.4 tons/acre/year). The trends in green weight growth over time (Figure 14) were very similar to volume growth.

Table 12. Analysis of variance results for loblolly pine average per-acre, total green weight at age eight.

Source	Type III F	Pr > F
Management	134.11	<0.0001*
Density	152.70	<0.0001*
Management x Density	1.45	0.2076

*Significant at α = 0.05.

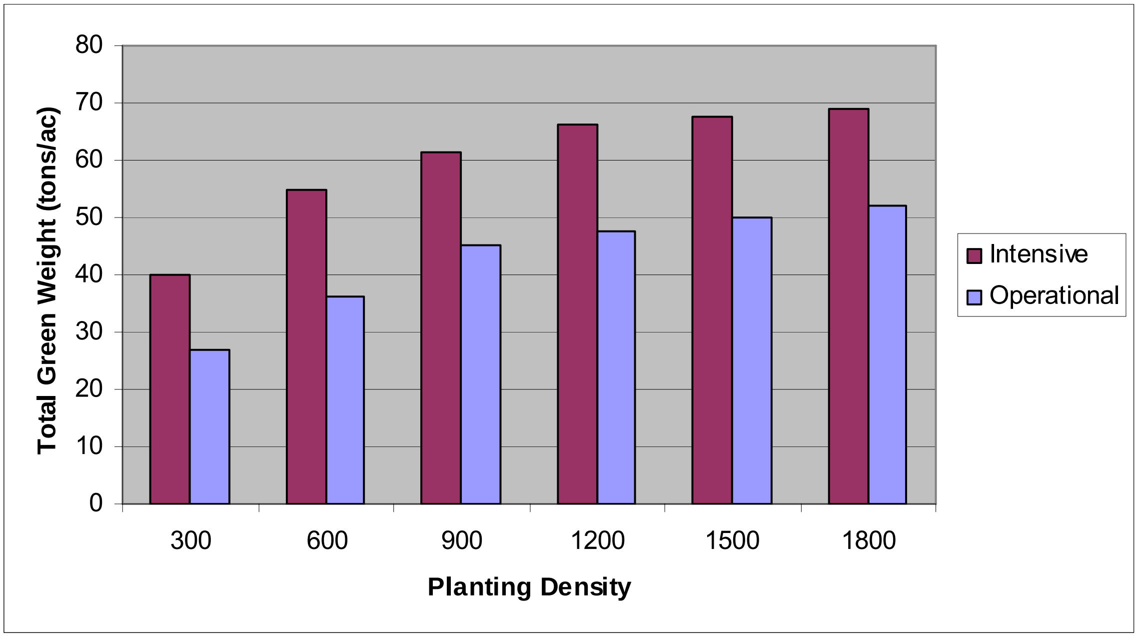

Figure 13. Average per-acre o.b. green weight by planting density and management intensity for loblolly pine at age eight.

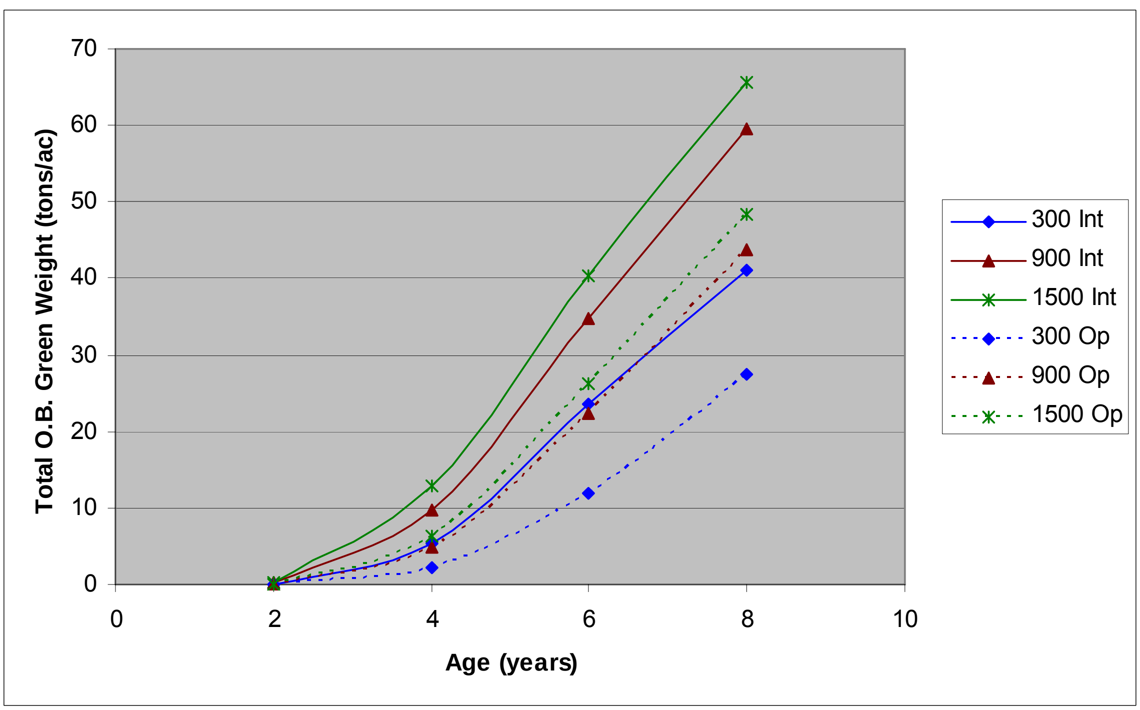

Figure 14. Average per-acre total green weight growth by planting density and management intensity for selected loblolly pine treatments.

3.8 Stand Density Index

Stand Density Index is a measure of the density of stands of trees that is independent of site index and age. For loblolly pine the limiting number of trees that can be found in a stand averaging 10 inches in DBH is 450.

Management intensity and density were significant factors for SDI (Table 13). Since both management intensity and initial density impact the speed of stand development, it is not surprising that they were significant factors. The effect of intensive management resulted in a 53 SDI unit increase on the average across all densities (Figure 15). The intensively-managed 1800 trees-per-acre plots have already reached 90.6% of the theorized maximum level for loblolly pine by age eight.

Figure 16 shows the natural logarithm of trees per acre (TPA) plotted over the natural logarithm of quadratic mean DBH (Dq) over time for all density/management treatments. Note that the operational plots begin behind the intensive plots. The intensive and operational plots then follow nearly identical tracts for a given density. The intensive treatment plots begin to approach the limiting density line between the ages of six and eight.

Table 13. Analysis of variance results for loblolly pine average stand density index at age eight.

Source	Type III F	Pr > F
Management	142.15	<0.0001*
Density	640.09	<0.0001*
Management x Density	0.88	0.4943

*Significant at $\alpha = 0.05$.

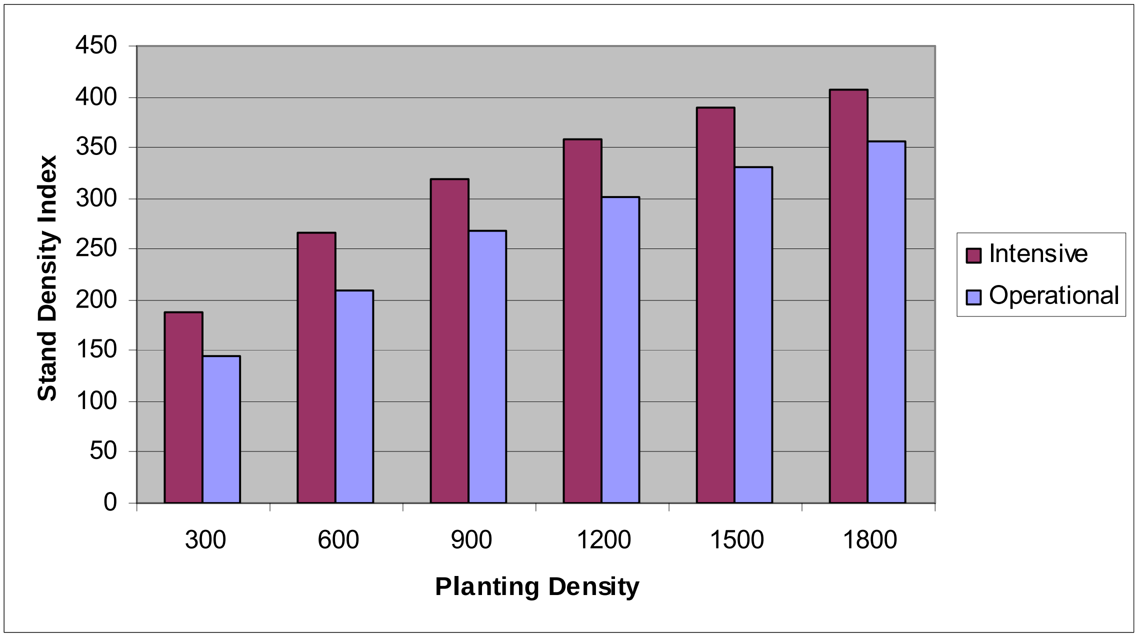

Figure 15. Average stand density index by planting density and management intensity for loblolly pine at age eight.

3.9 Relative Spacing

Another limiting density value often calculated is relative spacing. Relative spacing is the average distance between trees expressed as a proportion of the dominant height. RS asymptotes are species-specific and values for slash and loblolly have been empirically determined to be about 0.12. Relative spacing values were calculated for each plot in the study and an analysis of variance was conducted on the RS proportions. The average RS proportions by density, management intensity, and their interaction were significant factors for RS (Table 14). A plot of RS across initial densities and management intensities shows that RS decreased as initial density increased, that intensively-managed stands had lower RS values than operational stands for the same initial density, and that there was less difference between operational and intensively-managed stands at high densities than at lower densities (Figure 17).

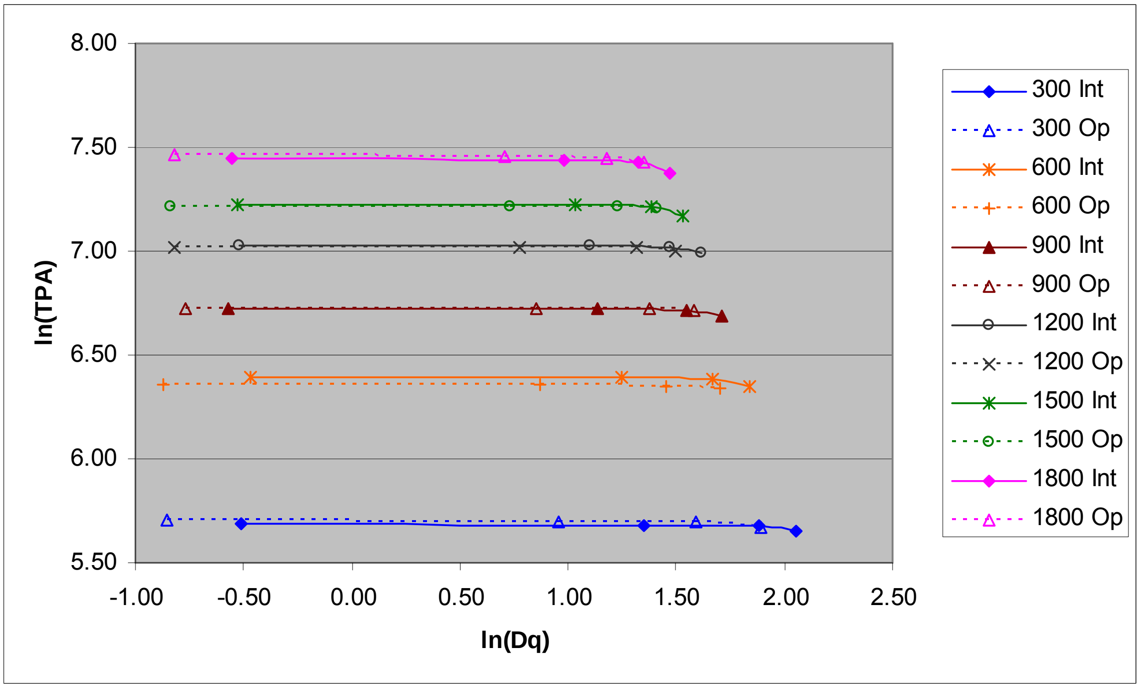

Figure 16. Natural log of trees per acre over natural log of quadratic mean DBH over time for all loblolly pine treatments.

Table 14. Analysis of variance results for loblolly pine average relative spacing at age eight.

Source	Type III F	Pr > F
Management	41.17	<0.0001*
Density	796.17	<0.0001*
Management x Density	3.54	0.0042*

*Significant at α = 0.05.

Relative spacing development over time for all density and management treatments is shown in Figure 18. Treatments above 600 trees per acre all have relative spacing values of less than 0.20 by the age of eight years. Intensive and operational treatments have similarly-shaped curves for a given initial density. The 1800 tpa intensively-managed plots had attained a relative spacing value of 0.15 by age eight.

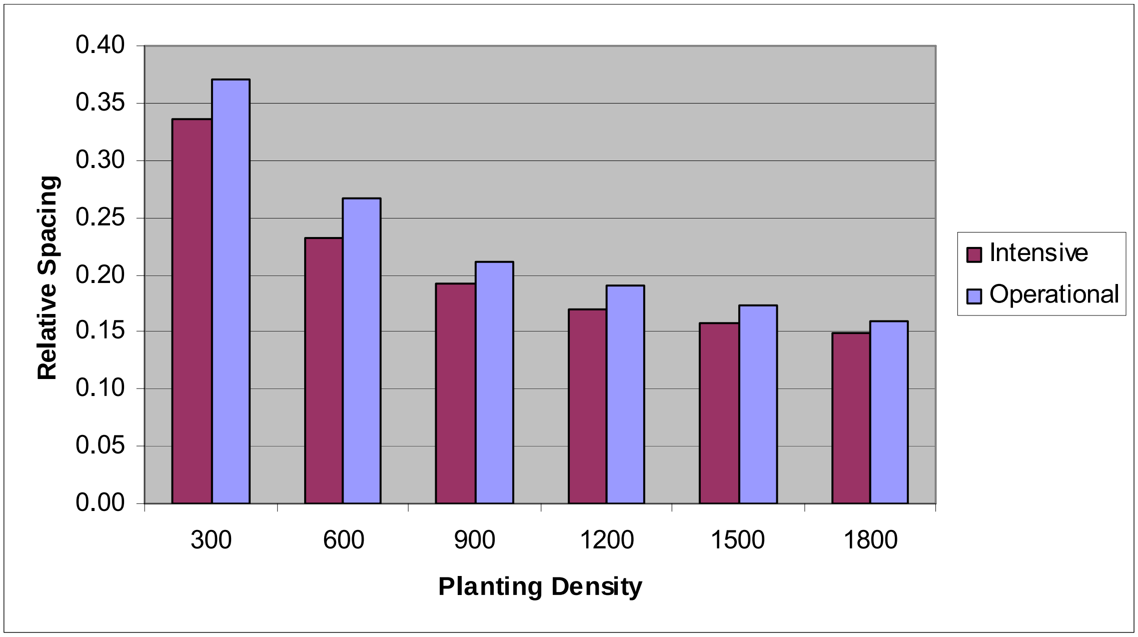

Figure 17. Average relative spacing by planting density and management intensity for loblolly pine at age eight.

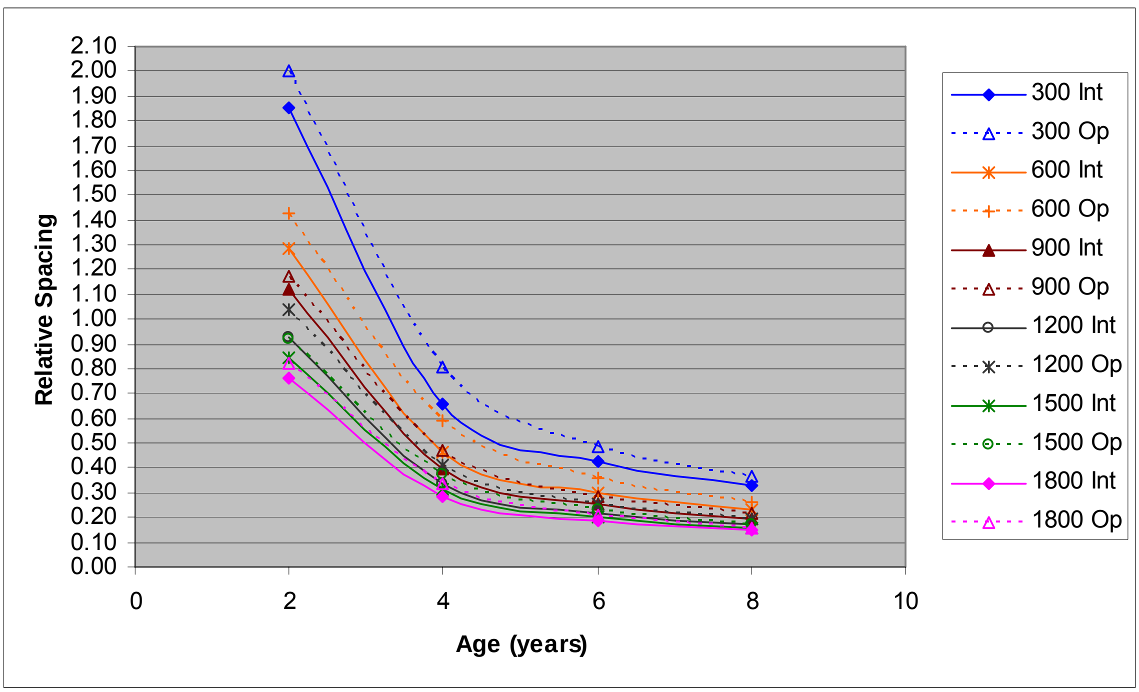

Figure 18. Relative spacing over time by planting density and management intensity for all loblolly pine treatments.

3.10 Crown Length

Length of live crown has long been considered an important indicator of tree growth and vigor. Live crown length has been used as a reliable predictor of diameter growth (Smith and Dubow, 1960) and of foliage biomass (Zhang, *et.al*., 2004) for loblolly pine. Management intensity, initial density and their interaction significantly impacted average crown length (Table 15). Average crown length decreased with increasing planting density. The intensively-managed plots had consistently higher crown lengths than operational plots but the management effect varied by initial density (Figure 19). Crown length development has slowed since age four and crown length has decreased for operational treatments of 1500 tpa and above and for intensive treatments of 900 tpa and above (Figure 20).

Table 15. Analysis of variance results for loblolly pine average crown length at age eight.

Source	Type III F	Pr > F
Management	9.97	0.0046*
Density	334.70	<0.0001*
Management x Density	5.59	<0.0001*

*Significant at $\alpha = 0.05$.

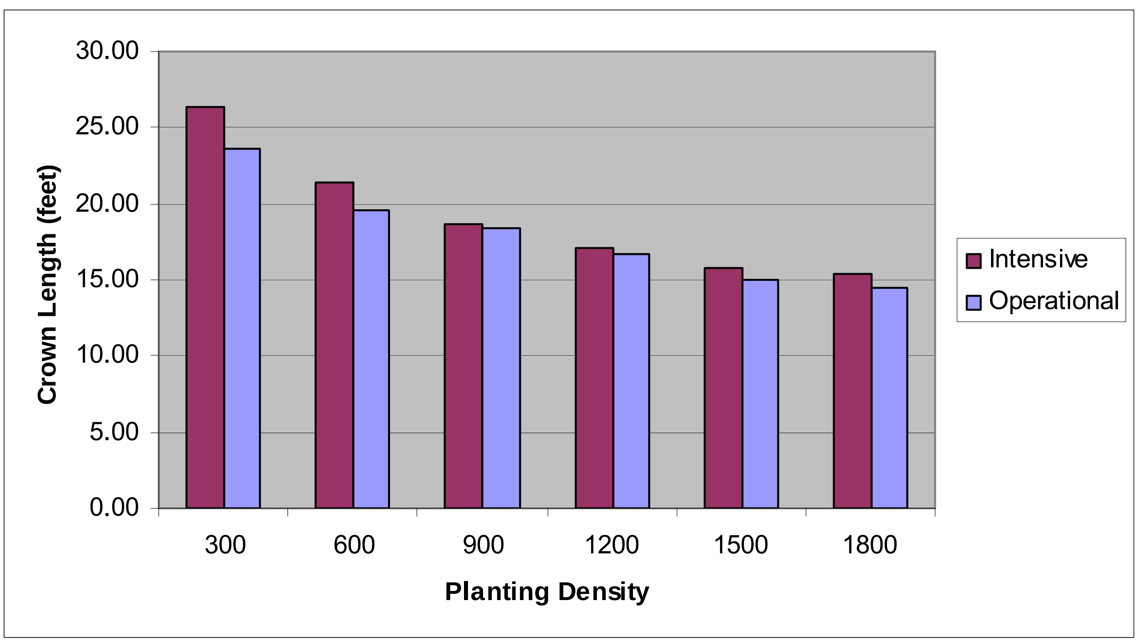

Figure 19. Average crown length by planting density and management intensity for loblolly pine at age eight.

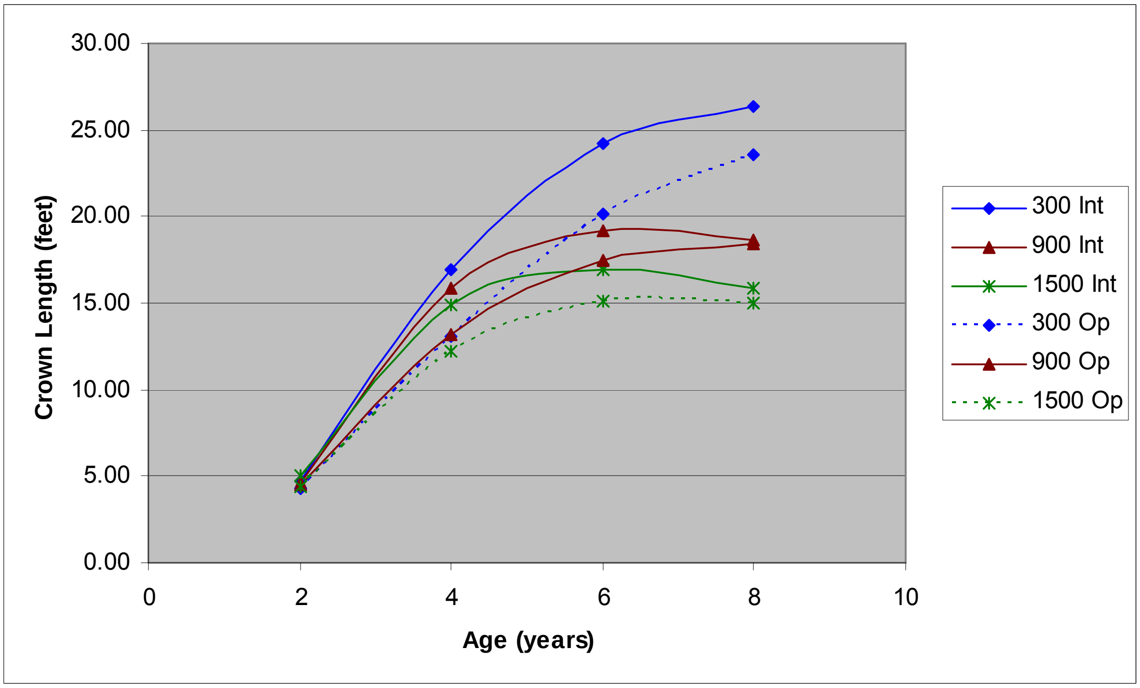

Figure 20. Crown length over time by planting density and management intensity for selected loblolly pine treatments.

3.11 Crown Ratio

Crown ratio is defined as the ratio of live crown length to the length of the entire stem and has long been used as an indication of a tree's vigor. Past research indicates that trees will grow satisfactorily if crown ratio is maintained at around 40%. A crown ratio below 30% indicates reduced vigor that will likely result in reduced diameter growth (Smith, 1962). Management intensity, initial density and their interaction significantly affected crown ratio (Table 16). Crown ratio steadily declined with initial density from a high of .72 at 300 tpa to a low of .45 at 1800 tpa (Figure 21). The operational treatments had higher crown ratios than the intensively-managed plots and this difference was greatest at the middle densities of 900 and 1200 tpa. Crown ratios have declined over time for all treatments and the rate of decrease has increased with increasing initial density and management intensity (Figure 22).

Table 16. Analysis of variance results for loblolly pine average crown ratio at age eight.

Source	Type III F	Pr > F
Management	12.74	0.0017*
Density	310.36	<0.0001*
Management x Density	2.90	0.0149*

*Significant at α = 0.05.

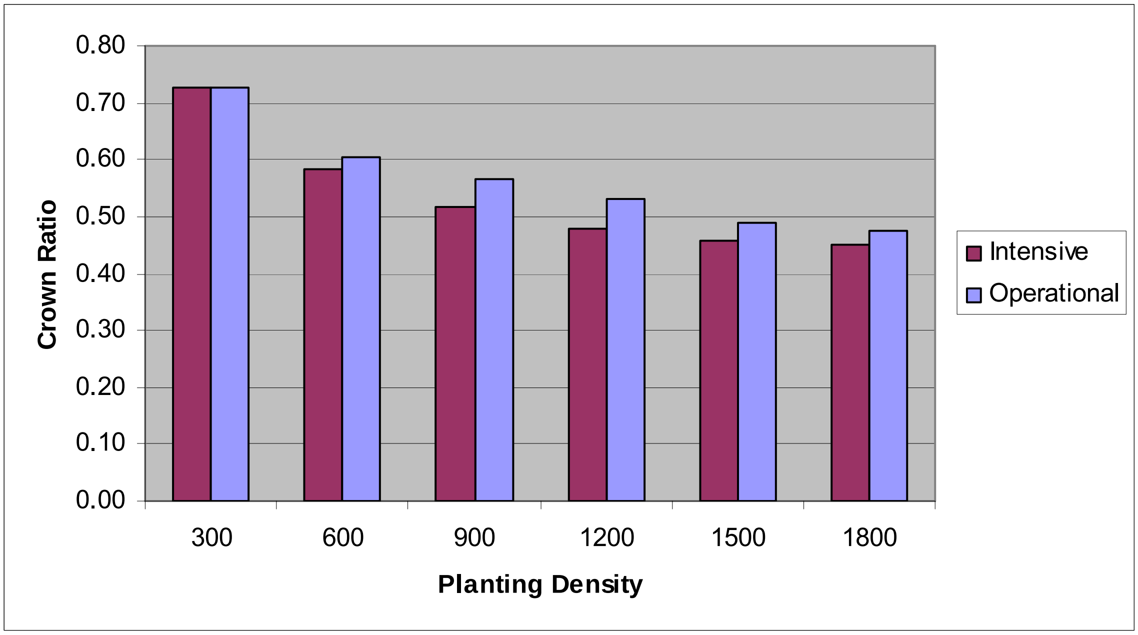

Figure 21. Average crown ratio by planting density and management intensity for loblolly pine at age eight.

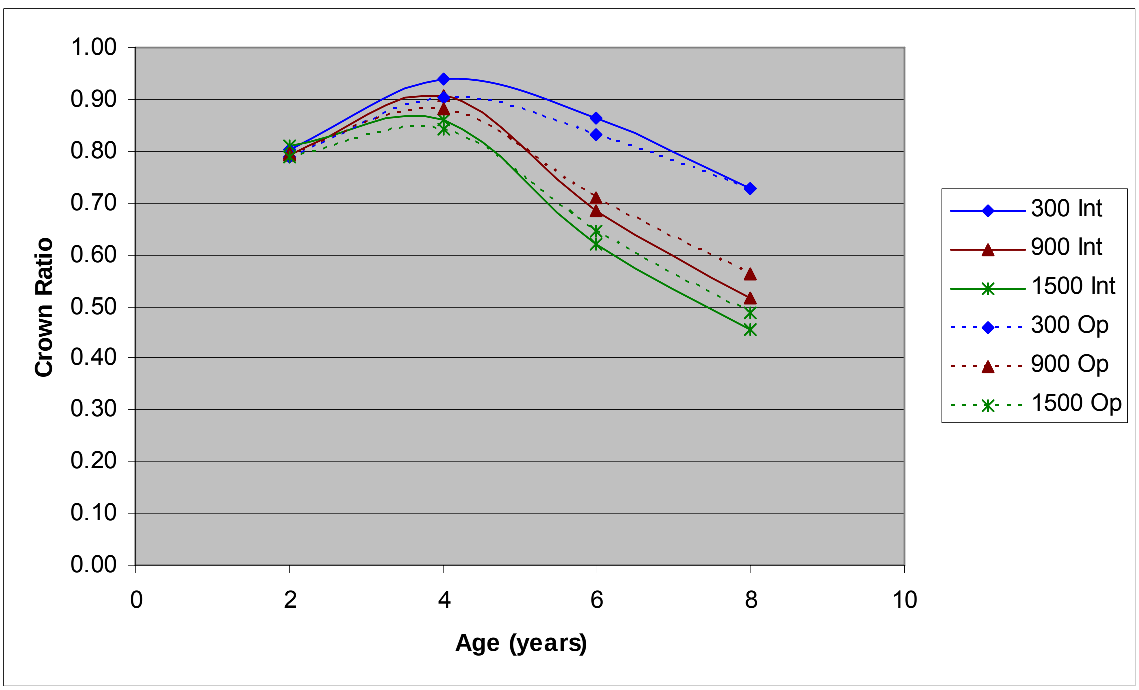

Figure 22. Average crown ratio over time by planting density and management intensity for selected loblolly pine treatments.

4 DISCUSSION AND CONCLUSIONS

Rapid growth for both the operational and more intensive treatment regime is reflected by age-eight stands with significant per-acre basal areas, green weights and total volumes. The relatively advanced stand development for age-eight plantations enhances the ability to examine developmental differences due to management treatment regime and planting density.

As with numerous studies reported in the literature, more intensive management has resulted in larger average DBH's for all spacing treatments. An examination of the average DBH's for the different spacing treatments showed that the additional weed control and fertilization accelerated the onset of inter-species competition on the intensive treatment plots. There were larger differences between average DBH between intensive and operational treatments at lower initial densities than at higher densities.

More intensive management significantly increased height growth at all spacing treatment levels. There was a relationship between initial density and both average height and dominant height with average heights being lower for higher initial densities beginning at about 1200 trees per acre. By age eight, these density-related differences were relatively small (2-3 feet).

On the negative side, more intensive management increased the cronartium infection rate over the operational treatment on the 300 trees per acre initial density. The relationship between increased growth and increased cronartium infection has been well documented so does not come as a surprise in this study. Perhaps more of a surprise is the trend of lower infection rates at higher initial densities. Overall, infection rates were very low.

Trends for per-acre basal area, green weight and total volume were nearly identical. All three attributes increased with increasing initial density. The more intensive management regime added about 28 ft^2 more basal area per acre, between 494 and 714 ft^3/ac more total volume, and between 13 and 19 tons/ac more green weight than the operational treatment regime. Charts of basal area, total volume and green weight development over time indicated that basal area growth has begun to slow down while volume and weight continued to increase linearly.

Reineke (1933) proposed a stand density index after noting that there was a limit to the number of trees of a given species that could be found in any pure stand of any given DBH. He proposed using 10 inches as the index DBH. For loblolly pine the limiting number of trees that can be found in a stand averaging 10 inches in DBH is 450. A few plots that exceeded this limit were observed in a spacing study (up to about 475), but mortality occurred and SDI was above 450 for only a limited time (Harrison, 2002).

In the SAGS Culture/Density study, SDI was affected by density and management intensity. Many of the SDI values were relatively high for eight-year-old stands. The intensively-managed 1800 trees per acre plots reached 90.6% of the maximum level for loblolly pine. Plots of the underlying SDI relationship (ln(TPA) x ln(Dq)) over time illustrate the interaction between planting density and management intensity. Stands of a given density have followed a nearly identical track until ages six and eight when the intensively-managed plots began to approach the limiting density line.

Normally, stands of loblolly pine are in their late teens before they approach the limiting density line. Since some of the Culture/Density plots combine high initial trees per acre with intensive management, they can be expected to approach the line at an earlier age. This is of particular interest to us since one of our objectives was to determine if the carrying capacity could be increased and also if the stand would “crash” with high management intensity before reaching merchantability for some of the high densities. While it is too early to test these trees for wood quality, a possible solution to large juvenile cores and large branches that cause lumber degrade would be to grow stands with relatively high-intensity management, but at high initial densities.

Relative spacing was also calculated and there was a significant management intensity and initial density interaction. Relative spacing typically declines over time since early in the life of the stand there is little mortality. Therefore the numerator of the RS equation stays fixed and the denominator increases as trees grow in height. At some point, a combination of tree mortality and slowing height growth causes the RS proportion to approach a lower asymptote. Differences in relative spacing between management intensities were higher at lower initial densities than at higher densities. The intensively-managed plots with 1200-1800 initial density have already fallen below an RS of 0.2 and are approaching the expected asymptote for loblolly pine at age eight.

Live crown length and crown ratio are useful indicators of growth and vigor. Crown lengths increased with increasing management intensity and decreased with increasing density. Crown ratio values varied by density from a high of 0.72 at 300 tpa to a low of 0.45 at 1800 trees per acre. There were also significant differences due to management but the differences were relatively small and the operational treatments had consistently higher crown ratios. This is somewhat misleading since the intensively-managed plots had higher average heights and live crown lengths than the operational plots.

The limiting density relationships for these intensively-managed plantations have interesting implications when traditional management concepts are applied. Previous studies indicate that, for various species, density-related mortality begins to occur at 50-55% of a theorized maximum density (Drew and Flewelling, 1979; Dean and Baldwin, 1993). It has therefore been recommended that thinning occur when the percent of maximum SDI reaches that level in order to capture potential mortality before it occurs (Harrington, 2000). For the SAGS Culture/Density study, the average %maximum SDI for intensively-managed plots is above 55% at 600 tpa and above, and the maximum percent mortality by age eight is only about 14%. Also, the lowest crown ratio (0.45) indicates that the trees should continue to grow vigorously. This is fortunate since small average diameters and poor wood quality make thinning economically infeasible at this young age.

Similar studies have been established in the Lower Coastal Plain region of Georgia and Florida (Harrison, *et.al.*, 2006) and in the Western Gulf region (Mohd, *et.al.*, 2006). The Lower Coastal Plain study showed similar results at age eight. More intensive management increased average DBH, average height, per-acre basal area, per-acre yield and cronartium infection level. Density also significantly affected all of the same factors except average height. The Western Gulf study began to exhibit similar trends at age two with respect to density and management intensity. Both the Lower Coastal Plain and Western Gulf studies included soil group as a factor. Soil group and soil group interactions had significant impacts in both of these studies.

Results from this study and others have yet to cause foresters in the Southeast to adjust expectations on limiting densities. The survival patterns and growth trajectories have, however, been drastically altered. This will have significant impacts on planting densities, timing and intensity of thinning and rotation ages. Future results from this study and others should help foresters refine management regimes to take advantage of the accelerated growth.

Results reported here and those obtained in the future will be used to:

- Validate and improve growth and yield systems,
- Develop approaches to improve stand density and thinning prescriptions,
- Evaluate strategies for producing specific product classes,
- Evaluate impacts on tree and wood quality.

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