SAGS CULTURE/DENSITY STUDY:
RESULTS THROUGH AGE 10

Plantation Management Research Cooperative
Warnell School of Forestry and Natural Resources
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EXECUTIVE 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 on the Piedmont and Upper Coastal Plain of Georgia, Alabama, Florida, Mississippi and South Carolina. 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 NH₄NO₃. At the beginning of the 4th growing season they received another 117 lbs/ac of NH₄NO₃, and at the beginning of the 6th growing season they received 300 lbs/ac of NH₄NO₃. At the beginning of the 8th and 10th growing seasons, operational and intensive plots received an additional 200 lbs/ac elemental N and 25 lbs/ac elemental P. Chemical tip moth control was applied on intensive cultural treatment plots using permethrin (Pounce®) two-three times before June in each of the first two growing seasons at labeled rate. The intensive cultural treatment plots received additional herbicide treatments to keep them as free of competing vegetation as possible throughout their rotation, and they also received additional...
Through age ten, crown length increased with increasing management intensity and decreased with increasing initial density. From age eight crown length began to decrease for both cultural regimes and all densities. The intensively managed plots had taller trees and longer live crowns. Management intensity effect on crown ratios, significant through age eight, was not significant (alpha = 0.05) at age ten.

Density related mortality began to take effect on higher density plots at age eight. The effect of management intensity on survival was significant at age ten; intensively managed plots had more mortality than operational plots. The intensively managed highest density plots reached the maximum SDI (450) for loblolly pine by age ten.
LIST OF FIGURES

Figure 1. Loblolly pine average DBH development over time by planting density and management intensity. .................................................................................................................................6

Figure 2. Loblolly pine average DBH by planting density and management intensity at age ten. ........................................................................................................................................................................6

Figure 3. Loblolly pine average height development over time by planting density and management intensity. ..........................................................................................................................7

Figure 4. Loblolly pine average dominant height development over time by planting density and management intensity. ...............................................................................................................8

Figure 5. Average height by planting density and management intensity for loblolly pine at age ten. ........................................................................................................................................................................8

Figure 6. Average dominant height by planting density and management intensity for loblolly pine at age ten. ................................................................................................................................................................9

Figure 7. Loblolly pine trees per acre trends by planting density and management intensity. ..........................................................................................................................................................10

Figure 8. Percent survival by planting density and management intensity for loblolly pine at age ten. ........................................................................................................................................................................10

Figure 9. Loblolly pine average percent cronartium infection by planting density and management intensity. ..........................................................................................................................................................11

Figure 10. Average percent cronartium infection by planting density and management intensity for loblolly pine at age ten. .....................................................................................................................................................12

Figure 11. Loblolly pine average per-acre basal area growth (ft²/ac) by planting density and management intensity. .....................................................................................................................................................................13

Figure 12. Average per-acre basal area (ft²/ac) by planting density and management intensity for loblolly pine at age ten. ..........................................................................................................................................................13

Figure 13. Loblolly pine average total per-acre outside bark volume (ft³/ac) by planting density and management intensity. .................................................................................................................................14
Figure 14. Average total per-acre outside bark volume (ft³/ac) by planting density and management intensity for loblolly pine at age ten

Figure 15. Average total per-acre stem green weight (tons/ac) by planting density and management intensity for loblolly pine

Figure 16. Loblolly pine average total per-acre outside bark green weight (tons/ac) by planting density and management intensity at age ten

Figure 17. Loblolly pine average stand density index by planting density and management intensity

Figure 18. Average stand density index (SDI) for loblolly pine by planting density and management intensity at age ten

Figure 19. Average relative spacing (RS) trends by planting density and management intensity for loblolly pine

Figure 20. Average relative spacing (RS) by planting density and management intensity for loblolly pine at age ten

Figure 21. Average crown length development by planting density and management intensity for loblolly pine

Figure 22. Loblolly pine average crown length (ft) for loblolly pine by planting density and management intensity at age ten

Figure 23. Average crown ratio by planting density and management intensity for loblolly pine

Figure 24. Loblolly pine average crown ratio by planting density and management intensity at age ten
**LIST OF TABLES**

Table 1. Soil groups used in the SAGS Culture/Density Study plots in the Piedmont........2

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

Table 3. Silvicultural treatments for SAGS Culture/Density study. ........................................2

Table 4. Spacing and plot size for the density subplots........................................................3

Table 5. Summary of ANOVA p-values for management intensity, density and their interaction for loblolly pine average DBH, average height, average dominant height, percent survival, percent cronartium infection, basal area per acre, total volume per acre, total stem green weight, stand density index, relative spacing, crown length, crown ratio at measured ages......................................................................................5

Table 6. Loblolly pine means by management intensity and planting density at age ten .........23
1 INTRODUCTION

Commercial 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 silvicultural 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 ten-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. Leaf area has been evaluated on selected locations and reported on by Will et al. (2005).

2 MATERIALS AND METHODS

2.1 Study installations

Twenty-three installations were established in the Piedmont and Upper Coastal Plain regions of Georgia, Alabama, Florida, Mississippi and South Carolina. The study was stratified over seven broad soil classes, four in the Piedmont and three in the Upper Coastal Plain (Tables 1 and 2). All 23 installations were viable throughout the ten year period.

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

<table>
<thead>
<tr>
<th>Subsoil Parent Material / Topsoil Depth</th>
<th>Montmorillonite / Mixed Clay &lt; 3 inches</th>
<th>Montmorillonite / Mixed Clay &gt; 3 inches</th>
<th>Kaolinite &lt; 3 inches</th>
<th>Kaolinite &gt; 3 inches</th>
</tr>
</thead>
</table>

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

<table>
<thead>
<tr>
<th>Drainage Class / Argillic Horizon Depth</th>
<th>Moderately well to well drained &lt; 20 inches</th>
<th>Moderately well to well drained 20-40 inches</th>
<th>Moderately well to well drained &gt; 40 inches</th>
</tr>
</thead>
</table>

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

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Operational</th>
<th>Intensive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Site Preparation</td>
<td>High-rate broadcast treatment in late summer/fall</td>
<td>High-rate broadcast treatment in late summer/fall</td>
</tr>
<tr>
<td>Mechanical Site Preparation</td>
<td>Optional, Cooperator select, applied to all plots</td>
<td>Optional, Cooperator select, applied to all plots</td>
</tr>
<tr>
<td>Fertilization</td>
<td>At Planting: 500 lbs/ac 10-10-10 Before year 8: 200 lbs/ac N + 25 lbs/ac P Before year 10: 200 lbs/ac N + 25 lbs/ac P</td>
<td>At Planting: 500 lbs/ac 10-10-10 After year 2: 600 lbs/ac 10-10-10 + 117 lbs/ac NH₄NO₃ + micronutrients Before year 4: 117 lbs/ac NH₄NO₃ Before year 6: 300 lbs/ac NH₄NO₃ Before year 8: 200 lbs/ac N + 25 lbs/ac P Before year 10: 200 lbs/ac N + 25 lbs/ac P</td>
</tr>
<tr>
<td>Weed Control</td>
<td>Year 1: 4 oz/ac Oust banded + directed spraying for hardwood control</td>
<td>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</td>
</tr>
<tr>
<td>Chemical Tip Moth Control</td>
<td>Growing seasons 1 &amp; 2: Pounce directly spraying 2-3 times at labeled rate before June</td>
<td></td>
</tr>
</tbody>
</table>
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, planting locations were double-planted and reduced to a single surviving seedling after the first growing season. The spacing and plot size for the density subplots are shown in Table 4. The genetic material used at each installation was selected by the PMRC cooperator. Planting material was considered good quality genetics at time of planting.

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

<table>
<thead>
<tr>
<th>Planting Density (TPA)</th>
<th>Spacing (ft. x ft.)</th>
<th>Trees per measure plot</th>
<th>Measure plot size (ac)</th>
<th>Gross plot size (ac)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1800</td>
<td>6 x 4</td>
<td>184</td>
<td>0.10</td>
<td>0.31</td>
</tr>
<tr>
<td>1500</td>
<td>6 x 4.8</td>
<td>160</td>
<td>0.11</td>
<td>0.32</td>
</tr>
<tr>
<td>1200</td>
<td>6 x 6</td>
<td>120</td>
<td>0.10</td>
<td>0.30</td>
</tr>
<tr>
<td>900</td>
<td>8 x 6</td>
<td>96</td>
<td>0.11</td>
<td>0.31</td>
</tr>
<tr>
<td>600</td>
<td>8 x 9</td>
<td>80</td>
<td>0.13</td>
<td>0.37</td>
</tr>
<tr>
<td>300</td>
<td>12 x 12</td>
<td>80</td>
<td>0.26</td>
<td>0.56</td>
</tr>
</tbody>
</table>

2.2 Measurements

Dormant-season tree measurements were collected at ages 2, 4, 6, 8 and 10 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. Each tree was also inspected for cronartium infection and tip moth damage. Total heights of unmeasured trees were estimated from the following height-diameter regression equation separately fitted for height measured trees at each measurement in each plot:

\[
\ln(HT) = b_0 + b_1 DBH^{-1}
\]

where \(HT\) = total tree height, DBH is tree diameter at breast height, and \(b_0\) and \(b_1\) are parameters to be estimated from each plot at each measurement.

Individual tree, outside bark cubic foot volumes and green weights with bark were calculated using the following equations from Pienaar et al. (1987):

\[
TVOB = 0.00401246 DBH^{1.829011} HT^{-0.969142}
\]

\[
GW = 0.110069 DBH^{1.935455} HT^{1.080621}
\]

where \(TVOB\) = total stem volume outside bark (o.b.) in \(ft^3\),

\(GW\) = 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 each measure age and the specified planting density that was imposed after the first growing season.

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

\[ SDI = N \left( \frac{10}{D_q} \right)^{-1.6} \]

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 at each measured age using the following equation:

\[ RS = \frac{\sqrt{43560/N}}{HD} \]

where RS = relative spacing; N = trees per acre surviving at RS age; and HD = average height of dominant trees.

### 2.3 Data Analysis

Analysis of variance (ANOVA) for a split plot design was used to test for significant sources of variation with the remeasurement data between the age of 2 and 10 years, respectively. The main plots are cultural treatments and planting densities are subplots. The split plot analysis was carried out using a mixed model. The installation and its interactions were regarded as random factors; the effects of cultural treatment, planting density, and cultural treatment \( \times \) planting density interaction were considered fixed. This approach allows for inferences across all sites represented by the sample of sites included in this study. The following hypotheses were tested: (1) there are no differences among cultural treatments; (2) there are no differences between planting densities; and (3) there are no cultural treatment \( \times \) planting density interactions. Analyses were conducted on average DBH, average height and dominant height, percent survival, percent cronartium infection, per-acre basal area, per-acre total volume, per-acre total stem green weight, stand density index, relative spacing, average crown length and ratio. All references to statistical significance refer to an alpha level of 0.05.

### 3 RESULTS

#### 3.1 Average DBH

Analysis of variance for average DBH indicated that management intensity factor was significant over the range of measured ages, density factor was significant except at age 2, and the management intensity \( \times \) planting density interactions was also significant at each measured age (Table 5). Average DBH development over time and average DBH at age ten by management intensity and initial density are sepratively shown in Figures 1 and 2.
Table 5. Summary of ANOVA p-values for management intensity, density and their interaction for loblolly pine average DBH, average height, average dominant height, percent survival, percent cronartium infection, basal area per acre, total volume per acre, total green weight, stand density index, relative spacing, crown length, crown ratio at measured ages.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Effect</th>
<th>Age 2</th>
<th>Age 4</th>
<th>Age 6</th>
<th>Age 8</th>
<th>Age 10</th>
</tr>
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<tbody>
<tr>
<td>DBH</td>
<td>Management</td>
<td>0.0001</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>0.9706</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>Management × Density</td>
<td>0.0474</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Average Height</td>
<td>Management</td>
<td>0.0003</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>0.1920</td>
<td>0.6977</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>Management × Density</td>
<td>0.0398</td>
<td>0.3451</td>
<td>0.4220</td>
<td>0.5177</td>
<td>0.5554</td>
</tr>
<tr>
<td>Dominant Height</td>
<td>Management</td>
<td>0.0003</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>0.1808</td>
<td>0.6062</td>
<td>0.0035</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>Management × Density</td>
<td>0.1621</td>
<td>0.4410</td>
<td>0.6154</td>
<td>0.5759</td>
<td>0.6149</td>
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<tr>
<td>Percent Survival</td>
<td>Management</td>
<td>0.4429</td>
<td>0.4204</td>
<td>0.7944</td>
<td>0.1272</td>
<td>0.0226</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>0.5310</td>
<td>0.5628</td>
<td>0.2650</td>
<td>0.0057</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>Management × Density</td>
<td>0.3458</td>
<td>0.5897</td>
<td>0.4983</td>
<td>0.2908</td>
<td>0.0310</td>
</tr>
<tr>
<td>Percent Cronartium Infection</td>
<td>Management</td>
<td>0.2684</td>
<td>0.0083</td>
<td>0.1260</td>
<td>0.1478</td>
<td>0.3571</td>
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<tr>
<td></td>
<td>Density</td>
<td>0.3491</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>Management × Density</td>
<td>0.4784</td>
<td>0.0005</td>
<td>0.0000</td>
<td>0.0005</td>
<td>0.1285</td>
</tr>
<tr>
<td>Basal Area Per Acre</td>
<td>Management</td>
<td>0.0003</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>Management × Density</td>
<td>0.0001</td>
<td>0.0000</td>
<td>0.0695</td>
<td>0.7059</td>
<td>0.1880</td>
</tr>
<tr>
<td>Total Volume Per Acre</td>
<td>Management</td>
<td>0.0007</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>Management × Density</td>
<td>0.0001</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.1661</td>
<td>0.4183</td>
</tr>
<tr>
<td>Stem Green Weight</td>
<td>Management</td>
<td>0.0009</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>Management × Density</td>
<td>0.0002</td>
<td>0.0000</td>
<td>0.0014</td>
<td>0.2044</td>
<td>0.4062</td>
</tr>
<tr>
<td>Stand Density Index</td>
<td>Management</td>
<td>0.0001</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>Management × Density</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0090</td>
<td>0.5399</td>
<td>0.2583</td>
</tr>
<tr>
<td>Relative Spacing</td>
<td>Management</td>
<td>0.0002</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>Management × Density</td>
<td>0.0843</td>
<td>0.0000</td>
<td>0.0009</td>
<td>0.0051</td>
<td>0.0246</td>
</tr>
<tr>
<td>Crown Length</td>
<td>Management</td>
<td>0.0003</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0046</td>
<td>0.0016</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>0.1650</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>Management × Density</td>
<td>0.0161</td>
<td>0.0009</td>
<td>0.0000</td>
<td>0.0001</td>
<td>0.1607</td>
</tr>
<tr>
<td>Crown Ratio</td>
<td>Management</td>
<td>0.0016</td>
<td>0.0007</td>
<td>0.0004</td>
<td>0.0017</td>
<td>0.0538</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>0.4430</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>Management × Density</td>
<td>0.0288</td>
<td>0.0017</td>
<td>0.0000</td>
<td>0.0149</td>
<td>0.3047</td>
</tr>
</tbody>
</table>
Figure 1. Loblolly pine average DBH development over time by planting density and management intensity.

Figure 2. Loblolly pine average DBH by planting density and management intensity at age ten.
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 than the operational plots. The difference in average DBH between the intensively managed plots and the operational plots was larger at lower initial densities.

### 3.2 Average Height and Dominant Height

For loblolly pine average height and dominant height, the management intensity factor was significant from age two; the density factor was significant from age six; there was no management intensity x density interaction at all measured ages (Table 5). Average height and average dominant height show similar trends by management intensity and initial density (Figures 3 and 4).

Average height and average dominant height at age ten by planting density and management intensity are shown in Figures 5 and 6, respectively. The intensively managed plots had larger heights than the operational plots; the intensive culture treatment increased average heights by between 3.2 to 4.2 feet, and increased dominant heights by between 3.1 and 4.0 feet, across the different densities. There was a consistent trend toward lower average heights and dominant heights at higher densities for both intensive and operational management; but this trend for height was not as obvious as for average DBH. The differences between management intensities by density in average heights were 3.1-3.7 feet, and the differences in dominant heights were 2.5.1-2.7 feet.

![Figure 3. Loblolly pine average height development over time by planting density and management intensity.](image)
Figure 4. Loblolly pine average dominant height development over time by planting density and management intensity.

Figure 5. Average height by planting density and management intensity for loblolly pine at age ten.
3.3 Percent Survival

Analyses of variance for percent survival indicated that the density factor had a statistically-significant effect on survival from age eight; while management intensity, density and management intensity interaction were significant only at age ten (Table 5). Survival trends indicate that density-related mortality has begun to take effect on the higher-density plots from age eight (Figure 7).

At age ten, the lowest average percent survival, observed on the intensively-managed 1800 trees per acre density, was 79.3%. Planting densities of 300-900 trees/acre averaged 90.3% survival for the intensively managed plots and 91.6% survival for the operational plots; while planting densities of 1200-1800 trees/acre averaged 82.3% survival for the intensively managed plots and 88.0% survival for the operational plots (Figure 8).
Figure 7. Loblolly pine trees per acre trends by planting density and management intensity.

Figure 8. Percent survival by planting density and management intensity for loblolly pine at age ten.
3.4 Percent Cronartium Infection

Management intensity was not significant except at age four; initial density was significant since age four; the management x density interaction significantly affected the cronartium infection rate over the period of ages 4-8 (Table 5). In general, there was a tendency for infection rate to decrease as density increased. Although average cronartium infection rate increased slowly over time, overall it was very low (Figure 9).

At age ten, average cronartium infection rates ranged from approximately 2.8 to 7.5% for all densities and management regimes (Figure 10). The intensive management treatment at 300 trees/ac initial density had the highest average infection rate and the 300 density also had the largest difference between intensive and operational management (also see Figure 9). As indicated in previous studies of loblolly pine, treatments that tend to accelerate diameter growth also tend to increase the cronartium infection rate (Zutter et al., 1987; Shiver and Harrison, 2000).

Figure 9. Loblolly pine average percent cronartium infection by planting density and management intensity.
3.5 Per-Acre Basal Area

Both management intensity and density significantly affected per acre basal area through 10 growing seasons; Initial density × management intensity interaction was significant at earlier ages 2 and 4, thereafter, the interaction was no longer significant (Table 5).

Basal area growth over time by planting density and management intensity is shown in Figure 9. It appears that all but the lowest densities have begun to slow down in basal area growth. Basal area increased with increasing density and the gain for intensive management compared to operational management was very consistent across densities (Figure 10). At age ten the densities of 1200, 1500 and 1800 trees/ac had 169 167 and 180 ft/ac basal area on the intensively-managed plots. Basal area gain for intensive management was significant and consistent across densities; gains for intensive management above operational ranged from 16.4 to 27.5 ft²/ac.
Figure 11. Loblolly pine average per-acre basal area growth (ft$^2$/ac) by planting density and management intensity.

Figure 12. Average per-acre basal area (ft$^2$/ac) by planting density and management intensity for loblolly pine at age ten.
3.6 Per-Acre O.B. Volume

The results of the analysis of variance for per-acre total stem volume showed nearly identical trends as seen for per-acre basal area where management and density significantly affected per-acre volume (Table 5). From age 8, the management × density interaction was not significant. Despite increases in mortality at higher densities, total volume continued to increase linearly through age ten for the treatments (Figure 11).

In general, total volume increased with increasing planting density (Figure 12); except for the initial densities of 1200 and 1500 trees/ac which had similar volumes for either intensive or operational management. At age ten, the intensive management treatments resulted in an average per-acre total volume of 529 to 734 ft³/ac more than that of the operational treatments. Average volumes on the intensively managed plots on initial densities of 1200, 1500 and 1800 averaged 3482, 3398 and 3685 ft³/ac, respectively.

![Figure 13. Loblolly pine average total per-acre outside bark volume (ft³/ac) by planting density and management intensity.](image-url)
Figure 14. Average total per-acre outside bark volume (ft³/ac) by planting density and management intensity for loblolly pine at age ten.

### 3.7 Per-Acre O.B. Green Weight

The results of the analysis of variance for per-acre total green weight exhibited identical trends as seen for per-acre total volume (Table 5). Management and density significantly affected per-acre green weight; from age eight the management × density interaction was not significant. The trends in green weight growth over time (Figure 13) were very similar to volume growth.

Generally, total green weight per acre increased with increasing density for both operational and intensive management, except for the densities of 1200 and 1500 trees/ac (Figure 14). The gain from intensive management over operational management averaged 17 tons/ac over all initial densities at age ten, the same as observed at age eight. The 1200 to 1800 intensive management plots averaged 84-91 tons/ac at age ten (mean annual increment of about 8.7 tons/acre/year).
Figure 15.  Average total per-acre stem green weight (tons/ac) by planting density and management intensity for loblolly pine.

Figure 16.  Loblolly pine average total per-acre outside bark green weight (tons/ac) by planting density and management intensity at age ten.
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, and their interaction was no longer significant beginning at age eight (Table 5). Since both management intensity and initial density impact the rate of stand development, it is not surprising that they were significant factors. Stand density index trends over time by initial density and management intensity are shown in Figure 15. From ages six or eight, most plots except for those with initial density of 300 trees/ac reached 55% of maximum stand density index (248), a possible thinning criteria.

The intensively managed 1800 trees/ac plots reached the theorized maximum SDI level (450) for loblolly pine by age ten (Figure 16). The effect of intensive management resulted in a 53 SDI unit increase at age eight and 37 SDI unit increase at age ten on average across all densities.

![Figure 17](image.png)

Figure 17. Loblolly pine average stand density index by planting density and management intensity for loblolly pine.
3.9 Relative Spacing

Another limiting density value often calculated is relative spacing (RS). Relative spacing is the average distance between trees expressed as a proportion of the dominant height. Relative spacing asymptotes are species-specific and values for 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 at all measured ages (Table 5).

Relative spacing development over time for all density and management treatments is shown in Figure 18. Treatments above 600 trees per acre all had RS values of less than 0.20 from age eight. Intensive and operational treatments have similarly-shaped curves for a given initial density. The 1800 trees/ac intensively-managed plots had attained a RS value of 0.13 by age ten. 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 18).

Figure 18. Average stand density index (SDI) for loblolly pine by planting density and management intensity at age ten.
Figure 19. Average relative spacing (RS) trends by planting density and management intensity for loblolly pine.

Figure 20. Average relative spacing (RS) by planting density and management intensity for loblolly pine at age ten.
3.10 Average 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 and initial density significantly impacted average crown length, and their interaction was no longer significant at age ten (Table 5).

Since age eight, crown length began to slow down or decrease for both intensive and operational treatments and for all densities (Figure 19). Average crown length decreased with increasing planting density. The intensively-managed plots had consistently higher crown lengths than operational plots (Figure 20).

![Average crown length development by planting density and management intensity for loblolly pine.](image-url)
3.11 Average 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 significantly affected crown ratio, initial density significantly affected crown ratio since age four, and their interaction was no longer significant at age ten (Table 5).

Crown ratios have declined over time for all treatments and the rate of decrease has increased with increasing initial density and management intensity (Figure 21). At age ten crown ratio steadily declined with initial density from a high of .62 at 300 tpa to a low of .40 at 1800 tpa (Figure 21). The operational treatments had higher crown ratios than the intensively-managed plots.
Figure 23. Average crown ratio by planting density and management intensity for loblolly pine.

Figure 24. Loblolly pine average crown ratio by planting density and management intensity at age ten.
3.12 Age 10 Stand Attributes and Thinning Potential

Characteristics of loblolly pine plantations at age ten are summarized in Table 6 by management intensity and initial density. As shown in Table 6, most plots meet potential thinning criteria.

Table 6. Loblolly pine means by management intensity and planting density at age ten. Values showed in red meet potential thinning criteria *.

<table>
<thead>
<tr>
<th>Management Intensity</th>
<th>Planting Density</th>
<th>Basal Area</th>
<th>SDI</th>
<th>Relative Spacing</th>
<th>Crown Ratio</th>
<th>Average DBH</th>
<th>Average Height</th>
<th>Crown Length</th>
</tr>
</thead>
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<tr>
<td>Operational</td>
<td>300</td>
<td>92.3</td>
<td>187</td>
<td>0.31</td>
<td>0.62</td>
<td>7.6</td>
<td>39.4</td>
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<td></td>
<td>600</td>
<td>119.2</td>
<td>263</td>
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<td>0.52</td>
<td>6.2</td>
<td>38.9</td>
<td>20.3</td>
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<td></td>
<td>900</td>
<td>132.1</td>
<td>307</td>
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<td>0.47</td>
<td>5.4</td>
<td>38.6</td>
<td>18.1</td>
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<tr>
<td></td>
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<td>0.42</td>
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<td>1800</td>
<td>163.6</td>
<td>418</td>
<td>0.14</td>
<td>0.41</td>
<td>4.2</td>
<td>35.7</td>
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<tr>
<td>Intensive</td>
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<td>224</td>
<td>0.28</td>
<td>0.62</td>
<td>8.6</td>
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<td>0.40</td>
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</tr>
</tbody>
</table>

* Potential thinning criteria: Basal Area >= 120 ft²/ac; SDI >= 248 (55% of Maximum SDI); Relative Spacing <=0.20; Crown Ratio <= 0.5.

4 DISCUSSION AND CONCLUSIONS

As with numerous studies reported in the literature, more intensive management has resulted in larger average DBH, average height and dominant height, crown length, per-acre basal area, per-acre total volume, and per-acre total stem green weight for all spacing treatments. Higher planting densities resulted in smaller average DBH, average height, and crown length; but larger per-acre basal area, total volume and green weight.

At age ten, the more intensive management regime added between 0.4 and 1.0 inches more average DBH, between 3.2 and 4.2 feet more average height, between 16 and 28 ft²/ac more basal area, between 529 and 734 ft³/ac more total volume, and between 15 and 20 tons/ac more green weight than the operational treatment regime.

After ten growing seasons, there were still larger differences in average DBH between intensive and operational treatments at lower initial densities than at higher densities. This is due to the fact that the additional weed control and fertilization accelerated the
onset of inter-species competition on the intensive treatment plots, as showed by examining average DBH for the different spacing treatments. The management and density interaction began to take effect on loblolly pine survival. The lower average percent survival was observed on the intensively-managed plots at higher initial densities than at lower densities. For relative spacing, management intensity and initial density interaction was still significant, and differences in relative spacing between management intensities were also higher at lower initial densities than at higher densities. For other characteristics, management and density interaction was no longer significant.

At the 300 trees/ac initial density, more intensive management increased the cronartium infection rate over the operational treatment. Overall, there were lower infection rates at higher initial densities. It seems that treatments that tend to increase tree diameter growth also tend to increase cronartium infection.

Trends for per-acre basal area, green weight and total volume were nearly identical. All three attributes increased with increasing initial density. Basal area growth has begun to slow down while volume and weight continued to increase linearly with age.

For loblolly pine the limiting number of trees that can be found in a stand averaging 10 inches in DBH is 450 (maximum stand density index). A few plots that exceeded this limit were observed in a spacing study (up to about 488), 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 ten-year-old stands. On average, the intensively-managed 1800 trees/ac plots reached 98.4% of the maximum level for loblolly pine, and the operational 1800 trees/ac plots reached 92.8% of the maximum level.

Relative spacing typically declines over time since early in the life of the stand there is little mortality. As result of tree mortality and slowing height growth, the RS proportion approaches a lower asymptote at some time point. The intensively-managed plots with 1200-1800 initial density have already fallen below an RS of 0.2 since age eight and are approaching the expected asymptote for loblolly pine at age ten.

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 0.62 at 300 trees/ac to a low of 0.40 at 1800 trees/ac at age ten. 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 percent maximum SDI for intensively-managed plots is above 55% at 600 trees/ac and above, and the
average percent mortality by age ten is already about 21% for the intensively managed 1800 trees/ac plots and about 13% for the operational 1800 trees/ac plots. Several plots had the crown ratio less than 0.40, which indicates that the trees could not continue to grow vigorously. These stand attributes with high planting densities and intensive culture illustrate the need for integrating planting density and silvicultural intensity with realistic and financially attractive thinning regimes.
5 Literature Cited


