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Culture and Density Effects on Tree Quality in Midrotation Non-Thinned Loblolly Pine Plantations

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Abstract: Six non-thinned loblolly pine (*Pinus taeda* L.) culture × density study sites in the Piedmont and Upper Coastal Plain of the Southeast U.S. were used to examine the effects of two cultural intensities and three planting densities on solid wood potential as well as the proportion and position of product-defining defects (forks, crooks, broken tops). A tree quality index (TQI) was used to grade stems for solid wood potential. The results show that an operational management regime exhibited a higher proportion of trees with solid wood product potential than did a very intensive management regime. Trees subject to operational management exhibited product-defining defects higher on the stem; however, the proportion of stems with defects was not significantly different from the intensive management. Planting densities of 741, 1482, and 2223 trees per hectare (TPH) exhibited a relatively narrow range of the proportion of trees with solid wood product potential that were not significantly different. Density did not have a significant effect on the heights of the product-defining defects. These results show that management intensity and less so planting density, affect the solid wood product potential indicators evaluated and should be considered when making management decisions.

Keywords: silviculture; solid wood product; product-defining defect

1. Introduction

Loblolly pine (*Pinus taeda* L.) is the most commercially important and widely planted plantation species in the southern United States. While demands for forest products vary over time and by region, management for a diverse mix of products including solid wood products is a common objective for many pine plantations in the southeastern United States [1]. For the successful production of solid wood products, pine plantations must be managed in a way to encourage both financially viable volumetric production and sufficient tree quality.

Of all the decisions made when establishing a plantation, the choice of initial planting density is one of the most important made by the forest manager as there is no one optimal density for every objective [2,3]. It is well known that planting density affects a variety of stand attributes. Higher density loblolly pine stands exhibit lower average breast height diameter, higher standing volume, and higher partitioning to stems and branches [4]. Studies examining the effects of planting density on average dominant height have shown mixed results. By age 16 in Virginia and North Carolina, loblolly pine grown at different densities showed significant differences in dominant height [2]. Further, by age 13, loblolly pine grown at six different densities in Georgia exhibited significantly different dominant heights [5]. Conversely, by age 8, no significant difference in dominant height was found for loblolly pine densities between 988 and 2470 trees per hectare (TPH) [6]. In a rotation length unthinned slash pine (*Pinus elliotii* Engelm.) study in South Africa, no significant differences in dominant height were found between the planting densities of 914 to 2964 trees per hectare [7].

Density management through thinning is a common practice. Non-thinned stands develop differently than their thinned counterparts. Non-thinned stands are characterized by significantly more mortality due to intraspecific competition [8]. A loblolly pine thinning study conducted in southeastern Oklahoma found that at age 24, average diameter in non-thinned plots was significantly lower than for two levels of pre-commercial thinning intensity applied at age 9. While basal area per hectare and stem biomass of the thinned stands never reached those of the non-thinned control plot, the basal area and volume was spread across higher value products. Further, dominant height was similar across all thinning treatment levels [9]. Outside of loblolly pine's natural range in the Ozark Mountains in Arkansas, non-thinned plots exhibited less diameter growth relative to thinned plots but had greater stand volume growth [10]. In a region-wide loblolly thinning study, non-thinned plots contained smaller proportions of chip-and-saw and sawtimber than did thinned plots [11,12].

Nutrient limitations often exist in managed loblolly pine plantations. To correct these deficiencies, forest fertilization is a common practice used by forest managers [13]. Many studies have shown the growth gains through the addition of limiting essential elements including N, P, K, or other micronutrients [14–21]. Nutrient limitations often arise due to competing vegetation. Growth gains in loblolly pine plantations have been shown in response to the control of both herbaceous and/or woody vegetation [6,15–18,21–24].

While considerable advancements have been made in the productivity of southern pine, especially loblolly pine, there is limited research on how plantation culture such as competition control and fertilization, impact the stem quality of individual trees. Assumptions about the influence of plantation culture have been made; however, quantifying and evaluating stem quality have proven difficult. Questions have arisen concerning planting rectangularity and its effect on tree quality. A spacing trial in Virginia and North Carolina showed that for spacing ratios up to 1:3, there was no significant effect on stem quality [25]. Further, it has been shown that slower grown loblolly and shortleaf (*Pinus echinata* Mill.) trees exhibited higher stem quality [26], as did Scots pine (*Pinus sylvestris* L.) grown on less productive soils [27].

Genetics play a large role in loblolly pine stem quality. Decades of successful breeding in tree improvement programs have developed families that are fast growers, have strong resistance to disease, and are of higher stem quality relative to native stock [28]. Improved genetics have been shown to increase value for growers through improved growth, higher resistance to disease, and improved stem quality, despite their higher cost [29]. Improved genetics were also shown to have little genotype by environment interactions in terms of productivity [30].

Data: The South Atlantic Gulf Slope (SAGS) culture × density study was installed by the Plantation Management Research Cooperative (PMRC) at the University of Georgia in 1998 to study the combined effects of six levels of planting density and two levels of management intensity on loblolly pine stand development. The study was established across a wide geographic range covering the Piedmont and Upper Coastal Plain of the southern United States. The influence that both management intensity and planting density have on stand development is dramatic [31]. This study did not report on how the combined effects of planting density and culture intensity affect stem quality and the presence and position of product-defining defects. Consequently, the present research examines culture and density impacts on stem quality using a method to grade standing trees for their product potential. This system, termed the Tree Quality Index (TQI), is a simple and effective method used to operationally grade stems in many operational timber inventories.

Objectives: The overall goal of this study is to examine and quantify the effects of cultural practices and density management on tree quality. The specific objectives of this study are to 1: Determine the effect on stem quality resulting from two levels of management intensity and three different planting densities in non-thinned loblolly pine plantations, 2: Determine the effect on the position and proportion of product-defining defects resulting from two levels of management intensity and three different planting densities in non-thinned loblolly pine plantations, and 3: Project current

study conditions to age 30 to determine how management and density affect per hectare values at rotation age.

2. Materials and Methods

2.1. Site Description

This research utilized six loblolly pine installations of the South Atlantic Gulf Slope (SAGS) Culture Density study managed by the University of Georgia Plantation Management Research Cooperative (PMRC). Four of these installations are located in the Georgia Piedmont, one is in the Alabama Piedmont, and one is in the Georgia Upper Coastal Plain (Figure 1). All installations were on upland, well-drained sites common to this region. Standard tree measurements were taken at age 15, and tree quality assessments were completed during the 16th growing season. The expressed site index ranged from 21 to 27.1 m (Table 1) for stands planted at 1482 trees per hectare and which received operational culture.

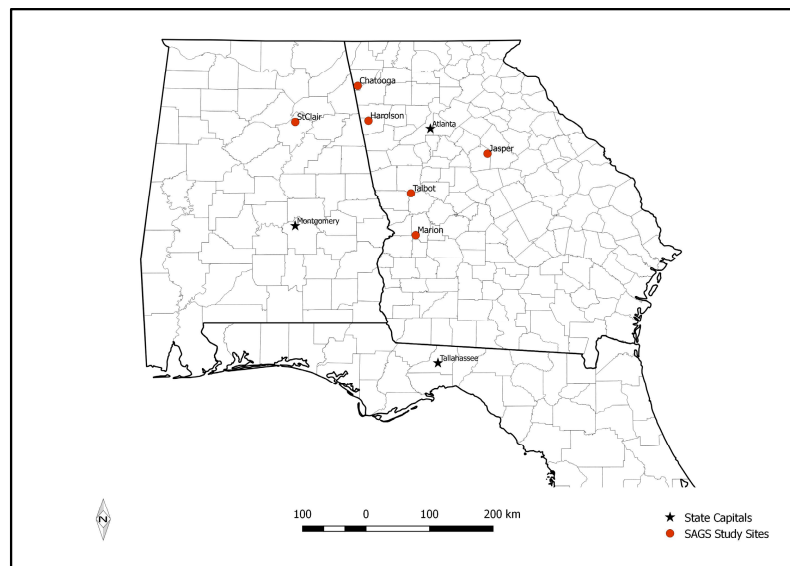


Figure 1. Location of non-thinned Plantation Management Research Cooperative (PMRC) South Atlantic Gulf Slope (SAGS) Culture × Density installations. (County name indicated at each site).

Table 1. Geographic details, soil details, and site index values for six Plantation Management Research Cooperative (PMRC) South Atlantic Gulf Slope (SAGS) Culture × Density non-thinned installations.

Installation	County	State	Physiographic Province	NRCS Soil Series	Soil Taxonomy	Site Index (m) ¹
5	Talbot	GA	Piedmont	Lloyd	Fine, kaolinitic, thermic Rhodic Kanhapludults	27.1
6	Marion	GA	Upper C.P.	Lakeland	Thermic, coated Typic Quartzipsamments	21
13	Jasper	GA	Piedmont	Lloyd-Pacolet	Fine, kaolinitic, thermic Rhodic Kanhapludults	25.6
16	St. Clair	AL	Piedmont	Conasauga Firestone	Very fine, mixed, active, thermic Chromic Vertic Hapludalfs	21.6
17	Harolson	GA	Piedmont	Grover	Fine-loamy, micaceous, thermic Typic Hapludults	25.6
18	Chatooga	GA	Piedmont	Fullerton	Fine, smectitic, thermic Vertic Paleudalfs	22.9

¹ Site index base age 25 is shown for trees subjected to operational culture and planted at 1482 stems per hectare. “NRCS”: Natural Resources Conservation Service. “GA”: Georgia. “AL”: Alabama. “Upper C.P.”: Upper Coastal Plain.

Three planting densities that have been used in commercial plantations were evaluated: 741, 1482, and 2223 trees per hectare. Two management intensities were tested: operational and intensive. The operational treatment consisted of early competition control and several fertilization treatments; the intensive treatment consisted of complete competition control throughout the entire rotation and numerous fertilization events (Table 2).

Table 2. Detail of cultural regimes utilized in the PMRC SAGS Culture × Density study through age 15.

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: 56 kg/ha N + 24.6 kg/ha P + 47 kg/ha K	At planting: 56 kg/ha N + 24.6 kg/ha P + 47 kg/ha K After year 2: 112 kg/ha N + 29.1 kg/ha P + 56 kg/ha K + micronutrients
		Before year 4: 44.8 kg/ha N
		Before year 6: 112 kg/ha N
	Before year 8: 224.2 kg/ha N + 28 kg/ha P	Before year 8: 224.2 kg/ha N + 28 kg/ha P
	Before year 12: 224.2 kg/ha N + 28 kg/ha P	Before year 10: 224.2 kg/ha + 28 kg/ha P Before year 12: 224.2 kg/ha + 28 kg/ha P Before year 14: 224.2 kg/ha + 28 kg/ha P
Competition Control	Year 1: 0.29 L/ha Sulfometuron methyl banded + directed spraying of glyphosate and tryclopyr for hardwood control	Year 1: 0.29 L/ha Sulfometuron methyl broadcast + directed spraying for complete competing vegetation control After year 1: 0.88 L/ha Arsenal broadcast To Date: Repeated directed spraying of glyphosate and tryclopyr for complete competing vegetation control

At each installation, one replication was established using a split-plot design. The main plots consisted of the two management intensities while the subplots consisted of the planting densities. Planting on each site occurred in 1998 with seedlings sourced by the PMRC cooperator controlling the installation. Genetically improved open pollinated stock was the common choice for plantations established in the late 1990's. At each planting location, seedlings were double planted and were reduced to one seedling after the first growing season. This ensured adequate survival for each installation. Plot size varied by planting density (Table 3), and each plot contained a measurement plot surrounded by a buffer approximately 7.9 m wide.

Table 3. Planting density plot sizes for the PMRC SAGS Culture × Density study.

Planting Density (TPH)	Spacing (m × m)	Trees Per Measurement Plot	Measurement Plot	Gross Plot Size (ha)
			Size (ha)	
741	3.66 × 3.66	80	0.105	0.227
1482	2.44 × 2.74	80	0.053	0.150
2223	2.44 × 1.83	96	0.045	0.125

2.2. Measurements

Diameter at breast height (DBH) was measured on every tree in the measurement plots to the nearest 0.254 of a centimeter (1/10th of an inch). Total height and height to live crown were measured on every other tree to the nearest 0.3 of a meter (1 foot). Those trees without measured heights were estimated using the following linear regression model (Equation (1)) with data collected from trees with measured heights for each plot. This linear regression model was fit to trees at different densities separately to avoid the possibility of a density effect on dominant height [32]. In this equation, β_0 is

the y -intercept, β_1 is the slope, ε represents the unknown error, H represents total height in meters and D represents diameter at breast height in centimeters:

$$\ln(H) = \beta_0 + \beta_1(D^{-1}) + \varepsilon \quad (1)$$

During the age 16 growing season, assessments of tree quality were made on all trees in the measurement plots. Trees were assigned a crown class as dominant/co-dominant, intermediate, or suppressed. Height to the lowest product-defining defect (stem fork, crook, broken top, disease, large branch whorl) was measured with a laser hypsometer to the nearest 0.3 m. Each tree was assigned a tree quality index (TQI). This is a partially subjective tree quality assessment that assigns trees a score on a 1 to 4 scale without 2 as an option (Table 4). Some versions of this method use a TQI 2 for stems with solid wood product potential but with moderate defects; however, this score is not used in this study for simplification.

Table 4. Tree quality index (TQI), specifications utilized for grading standing trees in the PMRC SAGS Culture \times Density study.

TQI Class	Specifications
1	No defects that would eliminate solid wood product potential. No product-defining defects below 4.88 m.
2	Not used in this study
3	Major defects that eliminate solid wood potential. Permanently classified as pulpwood.
4	Serious defects that eliminate all merchantability. Classified as cull.

The TQI score is a total tree evaluation that incorporates stem sinuosity, branching, product-defining defects, and disease. A score of 1 indicates that the tree has solid wood product potential and is free of any major defects including disease, crook, sweep, large knots and branches (approximately 7.5 cm or larger through ocular estimation), forks, or broken tops below 5 m. A tree was assigned a TQI 1 if there were none of the listed defections that would eliminate 5-m length solid wood product potential. A tree assigned a TQI 3 has major defects that eliminate all solid wood product potential. Once a tree has been assigned a TQI 3, the given tree is assumed to be pulpwood for the remainder of the rotation. A tree assigned a TQI 4 has major defects that will preclude any merchantability and is classified as cull. The same individual (observer) scored every tree. It is important to note that the TQI system scores tree product potential, not necessarily current product. Recording the reason for each tree assessment would have provided valuable information but was not done due to time constraints. An example would be a tree downgraded from a TQI 1 to a 3 because of large or excessive branching. Assessing how branches influence product potential is difficult with the TQI method and is its main limitation. This is due to the difficulty in assessing an individual tree's potential to self prune and grow over knots. While efforts have been made to model branching and knots in loblolly pine [33], further data on branching are needed to understand how specific management decisions affect the branching dynamics. Solid wood product potential is not limited to sawtimber. Log length (≥ 5 m) product potential for "super-pulp", chip-and-saw, or sawtimber qualify a tree as having solid wood product potential. If a defect was present in the lower 3 m of the stem that did not seriously affect the product potential, the height of the defect was measured and recorded (results not shown). An example of such a defect would be a fusiform rust gall at the base of the stem. Such a defect would commonly be removed in a harvest, and the remainder of the stem would be merchandized accordingly.

2.3. Analysis

TQI is an ordinal-based categorical measure rendering traditional methods like analysis of variance (ANOVA) inappropriate for analysis. TQI scores were transformed into a binary yes/no for solid wood product potential. A TQI score of 1 indicated yes and a 3 or 4 indicated no. The proportion

of stems in each plot that exhibited solid wood product potential was analyzed using Equation (2) where: \mathbf{y} represents the vector of the observed proportion of stems with solid wood product potential with link function $g^{-1}(\boldsymbol{\eta})$, \mathbf{X} represents the known design matrix for the fixed effects, $\boldsymbol{\beta}$ represents the vector of unknown fixed effects parameters, \mathbf{Z} represents the known design matrix for the random effects, and \mathbf{u} represents the vector of unknown random effects parameters.

$$E[\mathbf{y}|\mathbf{u}] = g^{-1}(\boldsymbol{\eta}) = g^{-1}(\mathbf{X}\boldsymbol{\beta} + \mathbf{Z}\mathbf{u}) \quad (2)$$

Equation (2) is a generalized linear mixed effects model (GLMEM) in which the management level and planted trees per hectare were designated as the fixed effects. The interaction terms that were found to be non-significant were not included in the final model specification. Installation, interaction of installation and management level, and interaction of planted trees per hectare and the interaction of installation and management were designated as the random effects through random intercepts. Although random slopes were evaluated, they did not improve the fit of the model when included and hence were removed. In this GLMEM, the response distribution is assumed to be binomial with a logit link function. Planted trees per hectare was designated as a factor to ensure convergence of the model.

Analysis of product-defining defects was considered for both the proportion of stems with these defects as well as the average height at which the defects occurred. The proportion of stems that exhibited a product-defining defect in each plot was also analyzed using a GLMEM (Equation (3)) in which \mathbf{y} represents the vector of the observed proportion of stems with product-defining defects, and all other terms are as described for Equation (2).

$$E[\mathbf{y}|\mathbf{u}] = g^{-1}(\boldsymbol{\eta}) = g^{-1}(\mathbf{X}\boldsymbol{\beta} + \mathbf{Z}\mathbf{u}) \quad (3)$$

The management level and planted trees per hectare were designated as the fixed effects. The interaction terms that were found to be non-significant were not included in the final model. Random effects were designated in the same manner as in the analysis of solid wood product potential. Planted trees per hectare was again designated as a factor to ensure model convergence. In this GLMEM, the response distribution is assumed to be binomial with a logit link function.

The average height of the product-defining defects in each plot was analyzed using a linear mixed effects model (LMEM), with management level and planted trees per hectare designated as the fixed effects (Equation (4)), in which \mathbf{y} represents the vector of observed plot product-defining defect heights, and $\boldsymbol{\varepsilon}$ represents the vector of unknown random errors. All other terms are as described in Equation (2).

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \mathbf{Z}\mathbf{u} + \boldsymbol{\varepsilon} \quad (4)$$

The interaction terms that were found to be non-significant were not included in the final model. Random effects were designated in the same manner as in previously described models. Due to large differences in the number of defects per plot, frequency weights were utilized in the model. Plots with more defects have a greater influence on the model than plots with much smaller numbers of defects.

To help demonstrate the impact of the effects of management intensity and planting density on product potential, pulpwood, top-wood, chip and saw, and sawtimber, green kilograms per hectare were calculated for each combination of management intensity and planting density. Two evaluations were performed, one including the TQI and product-defining defect values and one without these values. Product specifications can be found in Table 5. Total green weight, green weight to a specific diameter, and green weight to a specific height were determined using allometric weight equations (Equations (1), (7) and (8), respectively, in the original publication) proposed by [34]. These equations predict green weight in Imperial green tons. Allometric measurements including total height and diameter at breast height were not available at age 16; thus, age 15 measurements were utilized in conjunction with age 16 quality information. Green weight was converted to metric tons after estimation.

Table 5. Product specifications used in individual installation, management, and planting density combination product value calculations.

Product	Minimum DBH (cm)	Maximum DBH (cm)	Top Diameter (cm)	Minimum Length (m)	\$/Green Metric Ton
Pulpwood	11.43	20.32	7.62	4.88	11
Chip-and-saw	20.32	31.75	15.24	7.32	16.5
Sawtimber	31.75	101.6	20.32	4.88	27.6

DBH: Diameter at breast height.

Once age 16 product weights were calculated, a generalized stand table projection procedure was utilized to project the tree list to age 30. The FASTLOB mortality function [35] was utilized to model plot mortality.

Using the FASTLOB mortality function, the stand table was carried from age 16 to rotation age using the generalized stand table projection (GSTP) procedure described in the PMRC Technical Report 2004-4 [36]. The same allometric weight equations proposed by [34] were utilized to compute product metric tons per hectare after the projection. In the GSTP, the TQI and product-defining defects were carried through the projection. No thinning or additional management activities were assumed.

Analysis was conducted using the R statistical package [37]. Graphics were developed using the package ggplot2 [38]. All mixed effects models were fitted using the lme4 package [39]. All green weight calculations and growth projections, using equations previously described, were conducted using the proprietary “SMART” software from Smarter Forestry LLC, Bogart, GA, USA.

3. Results

3.1. Tree Quality Index

Management intensity affected the distribution of TQI scores. Intensive management reduced the proportion of stems that exhibited solid wood product potential (TQI 1) compared with the operational management regime (Figure 2). The proportion of stems subject to intensive management that exhibited some type of solid wood product potential was 0.79. The proportion of stems subject to operational management that exhibited solid wood product potential was 0.90. This difference was statistically significant at the $\alpha = 0.05$ level (henceforth used for all significance levels) with a p -value of <0.001 (Table 6). Planting density appears to have a less noticeable influence on the distribution of TQI scores. There was a slight decrease in the proportion of trees with TQI scores of 1 as density increased (Figure 2).

The proportion of stems subject to a 741 trees per hectare planting density that exhibited solid wood product potential was 0.863. The 1482 trees per hectare planting density exhibited a proportion of 0.855, while the 2223 trees per hectare planting density exhibited a proportion of 0.818. The differences in proportions among planting densities were not significant (p -value of 0.073, Table 6). No significant interaction between management intensity and planting density was observed for proportion of stems with solid wood product potential (p -value of 0.821). Hence, the interaction term was removed from the final model.

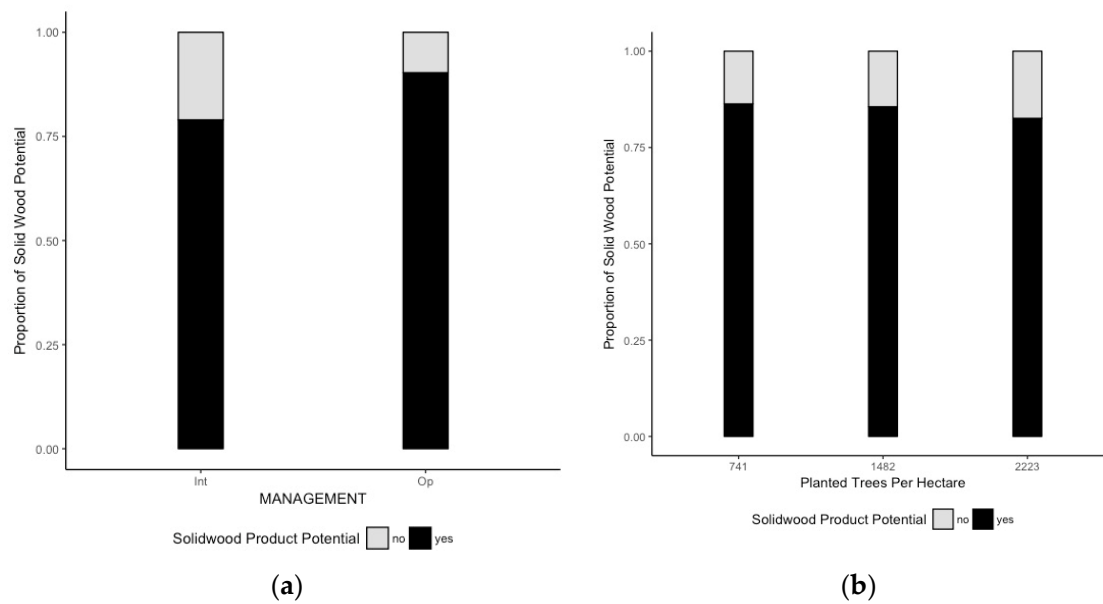


Figure 2. Proportion of solid wood product potential proportions by management intensity (a) and planting density (b) across six installations of PMRC SAGS Culture \times Density non-thinned sites (Int = intensive, Op = operational).

Table 6. Generalized linear mixed model, and linear mixed model analysis of deviance table (Type III Wald chi-squared tests) for analysis of solid wood product potential (Model 1), proportion of product-defining defects (Model 2), and heights of product-defining defects (Model 3). Models constructed without interactions. DF = Degrees of freedom, Man. = Management level, TPH = Trees per hectare.

Model		DF	χ^2 -Value	<i>p</i> -Value
Model 1	Intercept	1	50.545	<0.001
	Man.	1	47.135	<0.001
	TPH	2	5.243	0.073
Model 2	Intercept	1	19.071	<0.001
	Man.	1	2.938	0.087
	TPH	2	5.682	0.058
Model 3	Intercept	1	289.702	<0.001
	Man.	1	4.180	0.041
	TPH	2	3.183	0.204

3.2. Product-Defining Defects

The proportion of stems that exhibited product-defining defects increased for intensive management (0.21 vs. 0.17 for operational management, Figure 3); however, this difference was not statistically significant (*p*-value of 0.087, Table 6). The proportion of stems that exhibited product-defining defects decreased as trees per hectare increases (0.22, 0.18, 0.17 for 741, 1482, and 2223 densities, respectively, Figure 3).

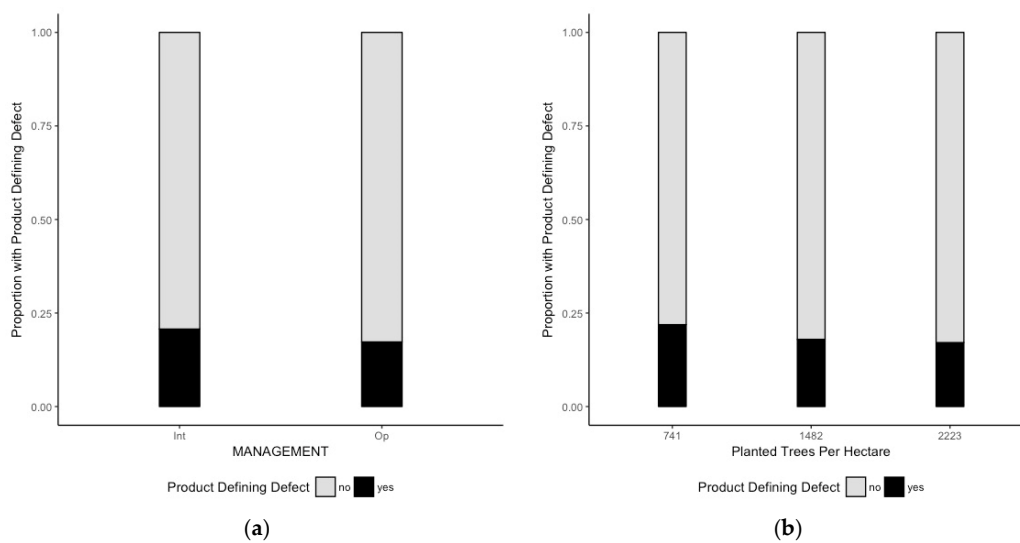


Figure 3. Product-defining defect proportion by management intensity (a) and planting density (b) across six installations of PMRC SAGS Culture × Density non-thinned sites (Int = intensive, Op. = operational).

These differences were not statistically significant (p -value of 0.058, Table 6). No significant interaction between management intensity and planting density was observed for the proportion of stems with product-defining defects with a p -value of 0.66. The interaction was removed from the final model. Stems subject to intensive management exhibited lower product-defining defect heights (8.60 m for intensive compared with 9.02 m for operational, Figure 4); this result was significant (p -value of 0.041, Table 6). No trend in average height was observed as density increased (8.56 m, 8.50 m, 9.33 m for 741, 1482, 2223 densities respectively, Figure 4), These differences were not significant (p -value of 0.204, Table 6). No significant interaction between management intensity and planting density was observed for product-defining defect height (p -value of 0.576) and was removed from the final model.

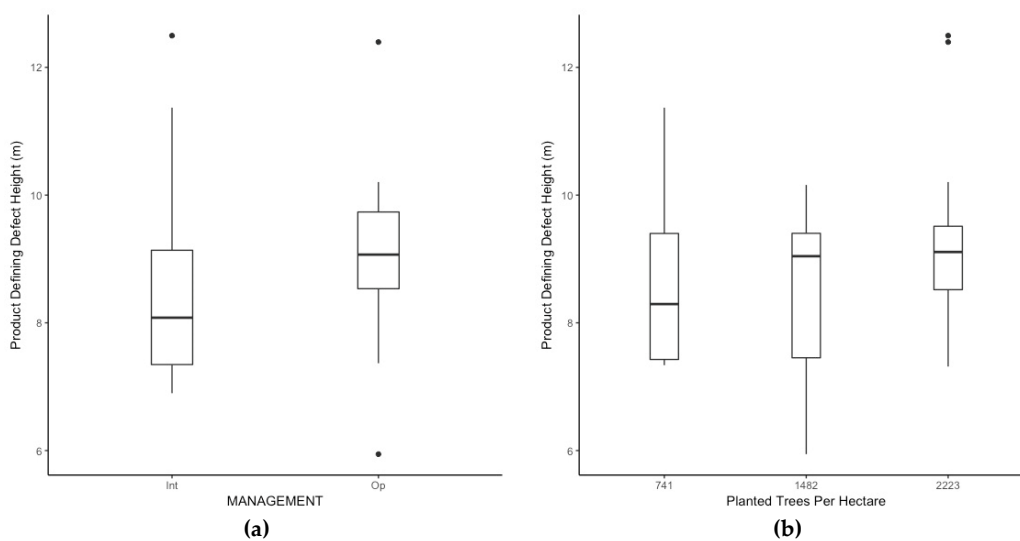


Figure 4. Product-defining defect height by management intensity (a) and planting density (b) across six installations of PMRC SAGS Culture × Density non-thinned sites (Int = intensive, Op. = operational). Outliers are displayed with a solid dot.

3.3. Product Value Impact

With the addition of quality characteristics (TQI values and product-defining defect heights), the value per hectare of every installation, management intensity and density combination decreased at age 16 and at age 30 (Figures 5 and 6) due to the stems not making sawtimber quality being categorized as pulpwood. Intensive management generally increased per hectare values at age 16 and age 30 (Figures 5 and 6).

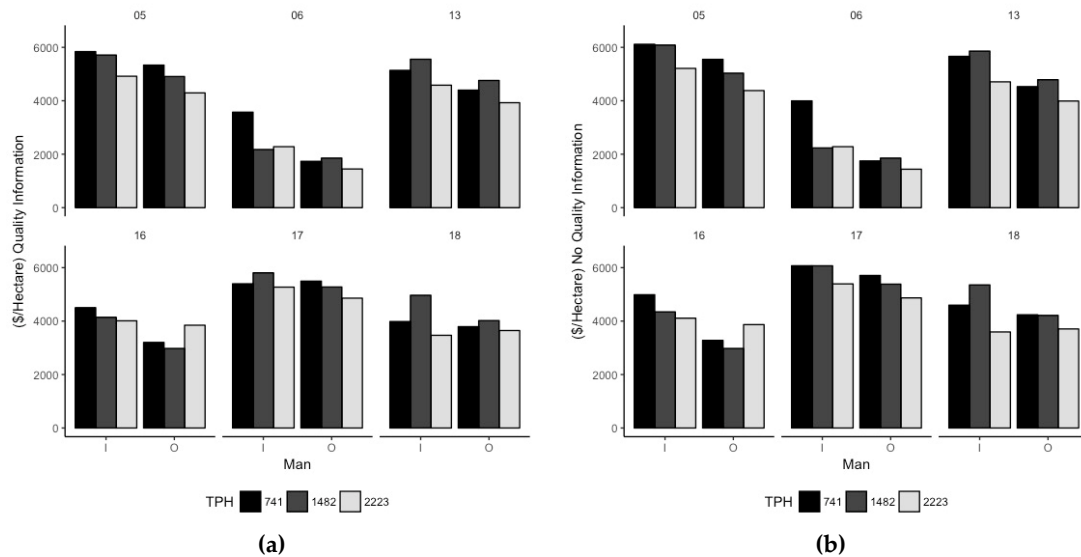


Figure 5. Age 16 standing timber value (U.S. \$/hectare) for each installation (installation number indicated above bars), management intensity (Man), and planted trees per hectare (TPH). Man “I” = intensive, “O” = operational. Value displayed with tree quality information considered (a) and without quality information (b).

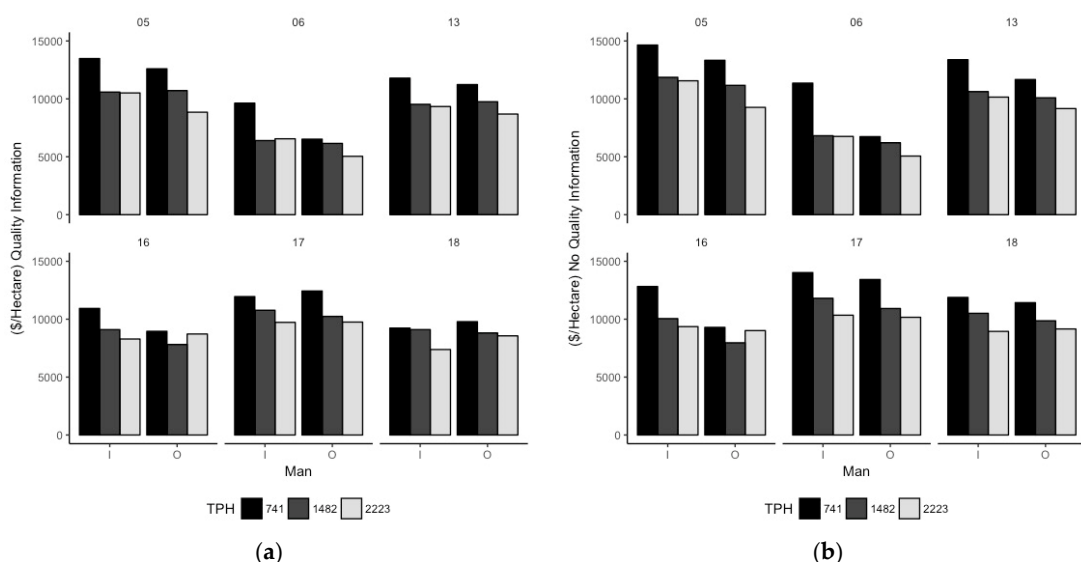


Figure 6. Age 30 standing timber value (U.S. \$/hectare) for each installation (installation number indicated above bars), management intensity (Man), and planted trees per hectare (TPH). Man “I” = intensive, “O” = operational. Value displayed with tree quality information considered (a) and without quality information (b).

At age 16, 33 plots subject to intensive management exhibited higher per hectare values than their operational management counterparts (Figure 7).

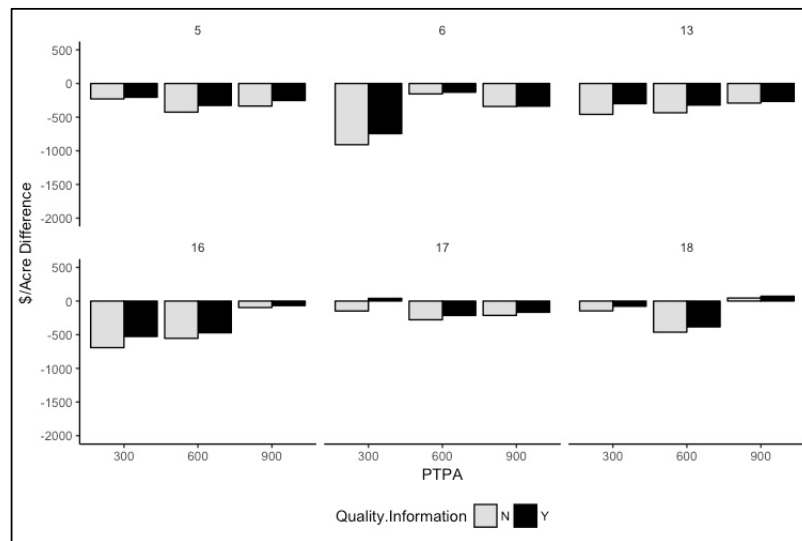


Figure 7. Difference in operational management and intensive management standing timber value (U.S. \$/hectare) at age 16 for each installation (installation number indicated above bars). Intensive management dollar value subtracted from operational for each planting density. Quality information includes the use of the TQI scores and product-defining defect heights. Negative values indicate a per hectare value greater for the intensive management regime than the complimentary operational management regime for the given planting density. “Y” = Yes, “N” = No.

By age 30, 28 plots subject to intensive management exhibited higher per hectare values than their operational counterparts (Figure 8).

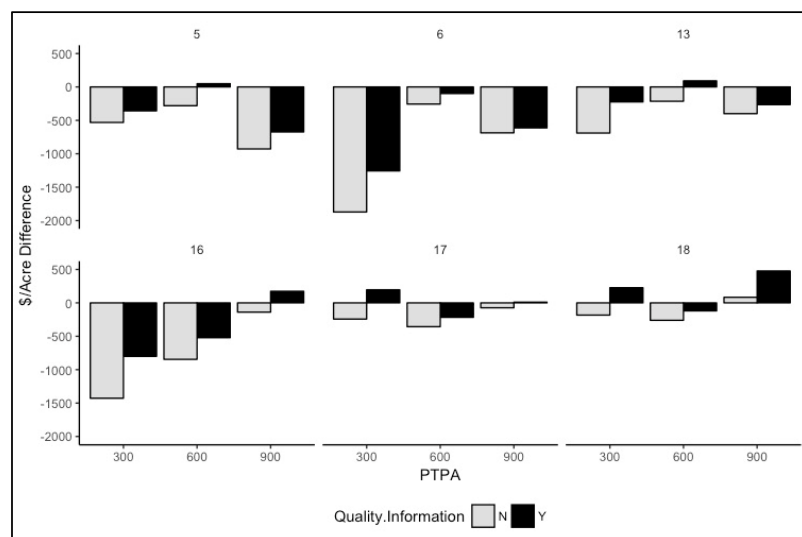


Figure 8. Difference in operational management and intensive management value standing timber (U.S. \$/hectare) at age 30 for each installation (installation number indicated above bars). Intensive management dollar value subtracted from the operational value for each planting density. Quality information includes the use of the TQI scores and product-defining defect heights. Negative values indicate a per hectare value greater for the intensive management regime than the complimentary operational management regime for the given planting density. “Y” = Yes, “N” = No.

4. Discussion

The SAGS study utilized was selected because of its large geographic range, the experimental design, and the amount of legacy data available. Further, the study is ongoing and has many similar replications across other geographic regions. This study provides a unique opportunity to examine the growth and development of loblolly pine across a portion of the native range at two levels of management intensity and six planting densities. For the purposes of this study, only the 741, 1482, and 2223 planted tree per hectare densities were examined. The 741 and 2223 tree per hectare densities are likely outside the commonly used planting densities; however, in this research, they represent the low and high ends of commercial planting densities.

The “operational” management regime attempted to model a high production regime used by commercial growers while the “intensive” regime attempted to remove any competition and nutrient limitations that the trees faced at a given site. In this study, more intensive management increased dominant height, basal area, and volume at every installation by age 15. The trees subject to the “intensive” regime grew under high soil nitrogen levels compared their “operational” counterparts. It has been shown that trees grown under high soil nitrogen develop significant stem sinuosity and that a proper nutrient balance is important for acceptable stem form [40]. The higher nitrogen inputs in the SAGS intensive culture may have led to significant reductions in tree quality. Further, it has been shown that increased management intensity increases the size of branches [41], which in turn, can reduce the potential for solid wood products. Branching effects on solid wood product potential was difficult to determine. However, given sufficient time, it is possible that many of the branches would self-prune and subsequently would be grown over with clear wood. The goals of the quality assessments in this study were to assess tree product potential independent of the traditional concept of a commercial rotation age for loblolly pine. The results of the current study show that more rapidly growing trees tend to exhibit a lower solid wood product potential; however, the intensive regime utilized is not realistic of commercial growing practices. If a more common, low intensity regime was compared to the operational regime in this study, differences in tree quality may have been less apparent. The effect of management intensity on product-defining defects was not clear. While intensive management resulted in a greater proportion of product-defining defects at a lower average height, the difference in proportion was not significant, whereas the differences in height were significant. The lack of significant differences in product-defining defect proportions and heights between management intensities indicates that solid wood product potential was more limited by stem form and branching and less so by defects such as forking and broken tops.

This information can be used to make more informed management decisions if high-value solid wood products are desired. While intensive management generally increased both mid-rotation and late-rotation per hectare values, often dramatically, it was not always the case. If the choice of a more intensive management results in a significant growth increase at a large expense of overall tree quality, the additional investment for the increased growth may result in a lower stand value at rotation age due to a reduction in stem quality. In the projection conducted on the individual installations (with stem quality information considered), there are multiple instances in which the operational regime for a given planting density is projected to have a higher, or nearly equal, stand value at age 30. In some areas in which loblolly pine is grown commercially, there are limited fiber markets, and the only available markets are those that purchase stumpage for the production of solid wood products. A major decrease in average tree quality would be especially detrimental for a grower in such an area. Due to widely varying costs of silvicultural prescriptions such as fertilizer, managers should carefully consider the tradeoffs between local treatment costs, stumpage markets and potential losses in solid wood product potential. While not considered for this study, it is common for thinning to be utilized to remove lower quality stems early in the rotation. The use of thinning is not ubiquitous in southeastern United States pine plantations, however. There are many examples of plantations grown to rotation age in which thinning is not utilized.

The effects of planting density on stem quality and product-defining defects are not clear. At the time of the measurements, the initial planting density did not appear to have a significant effect on overall stem quality, the proportion of product-defining defects, or the average heights of a product-defining defect. While higher density, non-thinned plantations exhibit smaller branches [41], the potential for a stem to effectively self-prune over the life of a tree has not been examined. As previously mentioned, judging the potential for self-pruning was difficult. Non-thinned, high planting density plantations are usually (though not always) managed for solid wood products with some form of thinning treatment. Thinning would be utilized to remove a portion of the stems and concentrate growth on the remaining, higher quality stems. Even so, it is interesting to observe the effects that initial density has on value per hectare by rotation age. With quality information considered, increased planting density tends to decrease rotation age value at both levels of management (Figure 6); however, the effect of density on stem quality cannot be established as the cause for this value decrease. Factors including different diameter growth and intraspecific mortality patterns may have contributed heavily towards the overall per hectare value.

The decrease in per hectare value after consideration of TQI values and product-defining defects highlights the importance of recording the quality information in a forest inventory. Forest managers are interested in both current as well as future standing value for reporting and planning purposes. Product tons produced using allometric measurements alone will not accurately represent true values and could result in inaccurate reporting and planning.

The solid wood product potential of an individual stem can be potentially reduced by a large number of contributing factors. The combination of the TQI assignments and the product-defining defect measurements is a simplified method of assessing the stem quality of standing trees. This reduction in data dimensionality increases field efficiency, simplifies analysis and provides managers with a more integrated measure of quality. Even so, the authors feel that the analysis may have benefited from more information to supplement the product-defining defect measurements and TQI quality assessments. Due to the partially subjective nature of any quality measure, independently auditing the assessments could add a level of rigor to the results presented.

5. Conclusions

This study utilized six non-thinned, loblolly pine culture x density installations to show the effects of two levels of management intensity and three planting densities on tree quality in the southeastern United States. The effect of intensive management significantly reduced overall tree quality and product-defining defect heights but not product-defining defect proportions. By age 30, some, but not a majority, of the plots subject to intensive management were projected to exhibit a lower per hectare value than their operational management counterparts. While the intensive management regime did not reflect common industry practices, based on the results of this study, forest managers should carefully consider the trade off between the costs of intensive management and the potential loss of overall tree quality. The substantial gain in growth from intensive management may be offset by treatment costs and a reduction in high value, solid wood product volumes in certain markets. The effects of different densities on stem quality and product-defining defects were not clear. No statistically significant differences were found for overall stem quality, proportion of stems with product-defining defects, and the heights of the product-defining defects. The results of this study, along with knowledge of other stand management and density effects, should provide managers with an increased ability to maximize value in managed loblolly pine plantations in the southeastern U.S.

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Conflicts of Interest: The authors declare the possible conflict of interest that the raw data cannot be released to the public due to the proprietary nature of the information, as it is from an industry research cooperative. The authors declare no other conflicts of interest.

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