CULTURE INTENSITY AND STAND DENSITY EFFECTS ON TREE QUALITY IN MIDROTATION LOBLOLLY PINE PLANTATIONS IN THE SOUTHEAST

by

PATRICK COREY GREEN

(Under the Direction of Michael Kane and Bronson Bullock)

ABSTRACT

Current loblolly pine (*Pinus taeda*) culture x density studies in the Piedmont and Upper Coastal Plain of the Southeast, the Plantation Management Research Cooperative (PMRC) South Atlantic Gulf Slope (SAGS) studies, were used to examine the effects of two cultural intensities, six planting densities, and their interactions on solid wood potential as well as the proportion and position of product defining defects. A tree quality index (TQI) and the current PMRC grading system, were used to grade standing timber for solid wood potential. Results show that operational management intensity produces a higher proportion of trees with solid wood product potential, higher product defining defect height, and lower proportions of product defining defects than does the intensive management in both non-thinned and thinned installations. The effect of planting density on tree quality was found to be minimal compared to management intensity when using both grading systems.

INDEX WORDS: Loblolly pine, Culture, Planting density, Thinning, Stem quality, Product defining defect, Product potential, Tree Quality Index, Tree form

CULTURE INTENSITY AND STAND DENSITY EFFECTS ON TREE QUALITY IN MIDROTATION LOBLOLLY PINE PLANTATIONS IN THE SOUTHEAST

by

PATRICK COREY GREEN

BS, University of Georgia, 2010

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2015

CULTURE INTENSITY AND STAND DENSITY EFFECTS ON TREE QUALITY IN MIDROTATION LOBLOLLY PINE PLANTATIONS IN THE SOUTHEAST

by

PATRICK COREY GREEN

Major Professor: Michael Kane
Bronson Bullock

Committee: Richard Daniels
Nicole Lazar

Electronic Version Approved:

Julie Coffield
Interim Dean of the Graduate School
The University of Georgia
May 2015

ACKNOWLEDGEMENTS

I would like to thank the University of Georgia, the Warnell School of Forestry and Natural Resources, and the Plantation Management Research Cooperative for their support on this research. I would like to extend many thanks to Derrick Gallagher, John Perren, and Miles Spong for their invaluable assistance in collecting data, and Mr. Eric Lowe and the PMRC field crew for all of their hard work and technical assistance. I would like to thank my advisory committee of Dr. Michael Kane, Dr. Bronson Bullock, Dr. Richard Daniels, and Dr. Nicole Lazar for their guidance and support. Finally, I would like to thank Mom, Dad, Cody, and my loving wife Lisa for their unwavering dedication and patience as I have worked on this research. I could not have done it without their love and support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Purpose of Study

Loblolly pine (*Pinus taeda*) is the most important commercial species in the southeastern United States. Years of research have led to dramatic increases in loblolly pine plantation growth rates. When loblolly pine has been grown out of its native range in areas such as Hawaii and South Africa, it became clear that the full growth potential of this species has not been achieved in its native environment (Borders and Bailey 2001; Harms et al. 2000). The role of improved genetics and improved silviculture techniques has led to loblolly pine growth rivaling that of fast growing species around the world and to come closer to its full biological growth potential (Borders and Bailey 2001). While great effort has been placed on growing southern pines faster, less research has been conducted on how culture and stand density affect stem quality. Stem quality is an important factor in determining the value of an individual tree. The purpose of this research is to study the effects that culture and stand density have on loblolly pine stem quality. This study will enhance our understanding of loblolly pine stem quality under a variety of stand densities and two levels of cultural treatment intensity. This study will evaluate a system, Tree quality index (TQI), to grade standing trees' product potential. While this system has a degree of subjectivity, it should provide understanding of the stem quality of trees in a stand. Also, stem height of product defining defects will be measured and average stopper height and proportion of trees with these defects will be analyzed. This study will also assess if thinning affects the proportions of trees that exhibit solid wood product potential. Finally, the TQI system will be compared with the current system used by the Plantation Management Research Cooperative (PMRC) to grade standing trees. The results from this study will help forest managers understand how both stand density and cultural intensity influence stem quality. This will lead to more informed decisions when establishing and managing pine plantations. This in turn should lead to management goals being more fully realized.

Thesis Structure

Chapter 1 ends with a literature review concerning management of southern pines as well as related literature concerning silviculture practices that effect stem quality from a variety of regions. Research of planting density and management intensity and their effects on tree quality in non-thinned stands is presented in Chapter 2. Research of planting density and management intensity and their effect on tree quality in thinned stands is presented in Chapter 3. Chapter 4 compares the current PMRC tree quality scoring system with the proposed TQI system. Conclusions for the entire study are presented in Chapter 5.

Literature Review

Loblolly pine

The southeastern United States is the leading producer of industrial timber of any region in the world (Allen et al. 2005). In the Southeast, loblolly pine (*Pinus taeda*) is the widest planted and most important commercial species. Loblolly pine responds very well to intensive management compared with other southern pine species such as slash pine (*Pinus elliottii*) and longleaf pine (*Pinus palustris*) (Shiver 2004). In the early 1950's, the few loblolly pine plantations in existence produced less than 90 cubic feet per acre per year. Current plantations are capable of producing in excess of 400 cubic feet per acre per year (Fox et al. 2004). With increasing worldwide demands for southern wood products and increasing interest in biodiversity in timberlands, significant research has been devoted to increasing loblolly pine's productivity.

Soils/Site

The choice of species when establishing a plantation is often based on the type of site that is desired to be planted. Some species are quite site specific while loblolly pine has been shown to perform well on a wide variety of sites and soils. Across 160 locations in the Southeast, loblolly pine yields were as high as or higher than slash pine on all soil groups (Shiver 2004). Site and soil characteristics are important for the forest manager when identifying stands in need of fertilization. Certain soils are naturally more fertile and suitable for pine growth than others. Many soils in the Southeast are infertile, often due to poor soil management practices of years past (Jokela 2004). The CRIFF soil classification system is a straightforward method of soil classification that has been developed to quickly classify soil. Being able to quickly determine the CRIFF classification can greatly assist the forester when making management decisions. The CRIFF system (Figure 1.1) uses soil drainage class, diagnostic horizons and depth to diagnostic horizons as a major means of classification (Jokela and Long 2000).

Genetics

The choice of genetic material is increasingly becoming more important. Choosing the correct genetic material should be a site specific decision (McKeand et al. 2006). Poor choices of genetics can lead to forest health issues, poor growth, and extreme cases, near total loss. Financially, careful selection of genetics has proven important. Choosing proper, superior genetics has been demonstrated to provide strong returns to landowners (McKeand et al. 2006). It is common practice to plant the best genetic material on the best sites because it should respond more favorably to the improved growing conditions than less improved genotypes (McKeand et al. 1997). There have been significant interactions of genotype x location, and genotype x silviculture demonstrated for loblolly pine (Roth et al. 2007).

Increasing both the volume and value of forest products is an important component of modern silviculture. Besides increased growth and disease resistance, genetics have also been shown to affect stem quality. Forking in loblolly pine is under fairly strong genetic control and loblolly pine growth cannot be maximized without influencing stem form (Xiong et al. 2014). In a study of 48 parents, family variation significantly affected traits that influence sawtimber potential (Cumbie et al. 2012). Uniform stands are often a desirable trait when utilizing intensive management. Improved genetics have been shown to not only increase growth rate and form quality, but also to improve overall stand uniformity (Aspinwall et al. 2011). Non-clonal genetic material was found to exhibit greater growth and improved tree quality compared with two different clonal varieties grown in the North Carolina Coastal Plain (Norman 2014).

Planting Density

One of the most important decisions facing a forest manager is the choice of planting density during plantation establishment (Amateis and Burkhart 2012). There has been extensive study concerning the choice of a planting density and the choice of spacing. It is well known that stands planted at higher densities will have lower average diameters than those planted on the same site at a lower density. Initial density has been shown to have little effect on growth of loblolly pine in the first several years after establishment. After the initial growth phase, average diameter, height, dominant height and survival were all found to be significantly affected by planting density (Zhao et al. 2010). In the Virginia Piedmont, higher planting density lowered loblolly pine average diameter (Carlson et al. 2009). Similar results of planting density effect on diameter have been reported for other species. Red alder was found to exhibit smaller diameters in northwest Oregon with higher planting densities (DeBell and Harrington 2002). Studies examining the effect of planting density on dominant height have shown mixed results. Average dominant height has been shown to not be significantly different among planting densities (Ware and Stahelin 1948; Pienaar and Shiver 1984; Amateis and Burkhart 2012). There are studies however that show dominant height being affected by planting density. In a study in southeastern Oklahoma, increased planting density resulted in a lower average dominant height (Hennessey et al. 2004). Similar results were found in the Lower Coastal Plain for different planting densities (Zhao et al. 2010). The choice of density affects the total above ground biomass. As loblolly pine density increases, above ground biomass has been shown to increase up to around 3700 trees/ha in 4 year old plantations. In high densities, differences in above ground biomass are no longer statistically significant (Burkes et al. 2003; Will et al. 2010). In 1995, a culture density study was established by The University of Georgia and the Plantation Management Research Cooperative (PMRC) to examine the effects of both planting density and culture intensity on loblolly pine growth in the South. By age 12, both management intensity and planting density significantly affected the growth of loblolly pine in the Lower Coastal Plain study. These affects were found to be additive in nature (Zhao et al. 2011). By age 12, more loblolly pine biomass was allocated to stem and bark at higher densities and intensive culture produced significantly more above ground biomass (Subedi et al. 2012). Planting density significantly affected above ground biomass partitioning for densities up to 2224 trees/hectare (900 trees/acre). The partitioning to stems and branches increased with higher planting density. In the same study, foliage density was significantly affected by planting density (Zhao et al. 2012). In the Upper Coastal Plain and Piedmont study, age 15 planting density had a significant effect on average diameter, basal area per acre, survival, and volume. Within operational planting densities of 300 and 600 trees per acre, average dominant height was not significantly affected (Wang et al. 2014).

Competing Vegetation Control and Fertilization

Controlling competing vegetation, both herbaceous and woody competition, has proven to increase pine productivity. There are many published studies showing the positive effects on loblolly growth from the control of competing vegetation. The control of herbaceous competing vegetation in young plantations increased both height and diameter growth of planted pines in a study conducted across the Southeast (Creighton et al. 1987). The complete control of competing vegetation dramatically increased growth in planted pines across a variety of sites in Georgia (Borders and Bailey 2001; Borders, et al. 2004). The removal of competing vegetation from established planted pine stands increased growth across sites in the Upper Coastal Plain of Georgia and Alabama (Fortson et al. 1996). Results from a slash pine study in the Lower Coastal Plain of Georgia and Florida reported similar results. Per hectare merchantable volume growth increased 15.2% after release from competing vegetation compared with control plots that received no release (Oppenheimer et al. 1989). Average dominant height was found to increase at three planting densities across a variety of sites with the addition of herbaceous weed control (Quicke et al. 1999).

Forest fertilization has proven to be a very effective method of increasing the growth of southern pine species. Even with higher fertilizer prices, fertilization is one of the most cost-efficient methods for forest managers to dramatically increase pine growth (Jokela and Long 1999). Loblolly pine stands that received annual fertilization were found to have dramatically higher MAI over the first 12 years of growth than those not receiving annual fertilization

(Borders and Bailey 2001; Borders et al. 2004; Kinane 2014). The addition of nitrogen and phosphorous was found to increase loblolly pine growth on three different soil series in the Lower Coastal Plain of North Carolina (Gent et al. 1986). Across a variety of CRIFF soil classes, the addition of year one fertilization was found to increase growth for both loblolly and slash pine in the Lower Coastal Plain of the Southeast (Jokela et al. 2000). While many studies have demonstrated the benefits of fertilizer additions on loblolly pine, additions of nitrogen, phosphorous, and potassium did not significantly increase height, diameter or volume growth in loblolly pine planted outside of its native range in the Ozark Mountains of Arkansas (Wheeler et al. 1982).

Commonly, competition control and fertilization are used together to increase southern pine productivity. Nearly additive growth effects were found for young loblolly and slash pine plantations through the combined use of fertilization and herbaceous weed control in the Lower Coastal Plain of the Southeast (Jokela et al. 2000). In studies receiving annual fertilization, less than additive responses were reported when using both competition control and fertilization (Borders and Bailey 2001; Will et al. 2002). This is likely due to excess nutrients and all nutrient related growth limitations having been met. A comparison of seven studies across the native loblolly range found that all sites that received fertilization and weed control responded positively to the treatments. Growth responses ranged from increases of 2-fold in Georgia to 3.5-fold in Florida (Jokela et al. 2004). The SAGS culture density study, installed across the South in 1998, further examined the combined use of different levels of fertilization and competing vegetation control on the growth of loblolly pine. Results through age 15 show that with increases in fertilization and vegetation control, average diameter, basal area per acre, average dominant height, crown length, and volume were all significantly increased. Survival was significantly decreased with a higher level of cultural intensity (Wang et al. 2014).

Mid-rotation fertilization and vegetation control are common techniques to enhance mid-rotation loblolly pine growth. Nitrogen is commonly limited by time of crown closure and some sites exhibit phosphorous limitations by this time. Competing vegetation controlled at plantation establishment may become re-established by mid-rotation. A region wide study examining the effects of mid-rotation N+P fertilization and release found that the treatment order in terms of biologic response was as follows: fertilization plus vegetation control > fertilization > vegetation control > no treatment. On sites in which limitations of other nutrient existed, vegetation control helped ameliorate these limitations in some cases (Albaugh et al. 2012).

Tillage

Fertilization and competition control are not the only means of affecting pine growth. Bedding is a common practice which is essential for pine survival on poorly drained sites (Gent et al. 1986). Bedding further concentrates topsoil and provides a degree of competition control (Nyland 2002). While bedding is now rarely used outside of the Lower Coastal Plain, bedding is an essential site preparation practice on poorly drained sites. Bedding keeps seedling root systems out of saturated soils and prevents low oxygen levels present during flooding or high water tables from killing seedlings. Other treatments including disking, chopping, windrowing, and a variety of other mechanical site preparation methods have been shown to have mixed effects on the growth of southern pines (Morris and Lowery 1988; Wheeler et al. 2002). Compared with other silviculture treatments such as fertilization and competition control, loblolly pine's response to tillage on upland sites was found to be minor (Carlson et al. 2006).

Thinning

Thinning provides many benefits to southern pine systems. Thinning provides remnant stems with more available resources and allows for greater diameter growth. Thinning artificially removes trees before density limiting conditions occur. Plantations growing under non-thinned conditions develop differently than those that receive thinning treatments. Non-thinned stand development is characterized by significantly more natural mortality due to intraspecific competition (Nyland 2002). Development of non-thinned stands is further characterized by smaller average diameters and often little effect on total heights. A thinning study conducted in southeastern Oklahoma found that in non-thinned plots, average diameter was significantly lower than on plots with two levels of thinning intensity at age 24 after a pre-commercial thin at age 9 (Hennessey et al. 2004). In this same study, thinning did not significantly affect average total height. While basal area per acre and stem biomass of the thinned stands never reached that of the non-thinned control plot, the basal area and volume was spread across higher value DBH classes. Outside of loblolly pine's natural range in the Ozark Mountains in Arkansas, non-thinned plots exhibited less diameter growth while having greater stand volume growth (Wheeler et al. 1982). Non-thinned stands arrive at overstocked conditions prematurely compared with thinned stands. Non-thinned plots in a shortleaf pine thinning study in Mississippi demonstrated heavy mortality once the stand reached 135 square feet/acre of basal area at age 28 (Williston 1983). A goal of many thinning operations is to concentrate growth onto larger, better formed trees to influence the end product proportions. Peelers, sawtimber, and other solid wood products are typically much higher valued products than fiber products. This leads many managers to use thinning as a tool to increase the yields of these higher valued commodities. In a region-wide loblolly thinning study, non-thinned plots contained smaller proportions of solid wood products than did the thinned plots (Amateis and Burkhart 2005).

Stem Quality

While there have been great advancements made in the productivity of southern pine, especially loblolly pine, there has been limited research on how silviculture affects the stem quality of individual trees. Many assumptions about the effects of silviculture have been made such as higher planting density improves stem quality. Quantifying individual stem quality, and the effects that silviculture practices have on stem quality has proven difficult. Methods for grading and predicting tree quality are varied. Tang et al. (1992) present a tree quality index (TQI) for grading standing planted loblolly pine in East Texas. A system for grading tree quality of immature southern pines was developed into a format similar to a dichotomous key (Belli et al. 1997). In tree quality studies, Amateis and Burkhart (2005) presented simple categories for tree classification. Trees were classified on a 1-3 scale with 1 meaning a tree qualifies as a "peeler", 2 meaning the tree qualifies for solid wood products including chip and saw or sawtimber, and 3 meaning the tree only qualifies as pulpwood. In this study, the probability of an individual loblolly pine attaining a certain product was found to be related to its diameter and whether or not the stand had been thinned. Another method to quantify stem form is through the use of the cylindrical form factor or CFF. This is defined as the ratio of tree volume to the volume of a cylinder of the same height with diameter equal to DBH. The CFF effectively characterizes the effects of fertilization on stem form (Jokela et al., 1989). In various regions across the loblolly pines range, trees were graded for product potential on a 1-4 scale with a 1 indicating a high quality crop tree, 2 a crop tree with minor defects, 3 a pulpwood tree, and 4 as a cull tree (Cumbie et al. 2012; Norman 2014).

In the Southeast, several studies have examined the effects of silviculture on the quality of southern pines. Across three different spacing arrangements in Louisiana, there was little difference in mean loblolly pine branch diameter and the number of branches (Baldwin et al. 2001). Fertilization of slash pine has been shown to affect stem form in northern Florida. By comparing the cylindrical form factor of non-fertilized stands with fertilized stands, the addition of nitrogen and phosphorous were shown to significantly influence stem form (Jokela et al. 1989). In plantation grown loblolly pine in southern Arkansas, artificial pruning was recommended to grow higher quality sawtimber when planted at lower densities (Guldin and Fitzpatrick 1991). Questions have arisen concerning planting rectangularity and its effect on tree quality. A spacing trial in Virginia and North Carolina showed that for spacing ratio up to 1:3, there was no significant effect on stem quality for loblolly pine (Amateis et al. 2004). It is commonly assumed that slower growing trees exhibit better stem quality. In uneven aged southern pine stands, lower productivity sites tend to carry trees with higher stem quality (Prestemon and Buongiorno 2000). While not the only consideration for tree quality, branch characteristics do factor into quality assessments. In the 7^{th} or 8^{th} growing season in the Lower Coastal Plain, Upper Coastal Plain, and Piedmont, 15 culture x density loblolly pine installations were evaluated for branch characteristics. Seven characteristics were evaluated: Average branch diameter, average branch basal area per tree, branch length, average branch angle, number of total branches, total number of live branches, and total number of dead branches. Reductions in branch size with an increase in initial planting density were observed. Further, the increase of culture was found to increase the average branch size. Lower initial planting density and higher levels of culture increased the total number of branches. The average branch angle was found to decrease with increases in planting density. Management intensity had minimal effects on average branch angle (Borders and Volfovicz 2010). Besides the work by Borders and Volfovicz (2010), there is no known research on the effect of the combination of stand density and culture on stem quality for southern pine systems.

The assumption that slower grown trees tend to exhibit better stem quality has been demonstrated outside of the Southeast. The quality of sawn Scots pine in Scandinavia was found inversely related to the radial growth of the stem (Ikonen et al. 2009). In a similar study in Sweden, it was shown that productive soils were found to produce lower quality Scots pine than low productivity soils (Teglemark 1999). A spike knot is a lumber defect that occurs when a branch grows at a very acute angle. Density effects on tree quality have been reported for several species. It is widely accepted that Sitka spruce planted a higher densities result in smaller knots (MacDonald and Hubert 2002). A study in Finland found that Scots pine planted at higher density exhibited fewer spike knots and exhibited straighter stems (Prescher and Stahl 1986; Stahl et al. 1990). Scots pine was found to have better straightness, smaller branch thickness, and fewer braches in Lithuania when planted at very high densities of 10,000 to 15,000 stems per hectare (Malinauskas 1999).

Introduction to Study

Knowledge about the effects of planting density and cultural intensity on southern pines are well documented and generally, well understood. Lacking however, is how density and culture affect stem form and quality of loblolly pine. Stem form and stem quality are primary drivers for an individual stem’s product classification and ultimately, its financial value at time of harvest. Understanding how stands of loblolly pine respond to core silviculture practices is a major goal of the SAGS culture density study. The goal of this research was to add another level of understanding on how stands of loblolly pine develop in the Piedmont and Upper Coastal

Plain of the southeastern United States. Both non-thinned and thinned installations across a wide range of sites and geographic provinces were considered along with four levels of planting densities and two levels of management intensity. This work provides insight into drivers of stem form and hopefully will lead to more research aimed at better understanding how silviculture practices influence the growth and quality of loblolly pine.

Literature Cited

Albaugh, T. J., Stape, J. L., Fox, T. R., Rubilar, R. A., and Allen, H. L. 2012. Midrotation vegetation control and fertilization response in *Pinus taeda* and *Pinus elliotti* across the southeastern United States. Southern Journal of Applied Forestry 36(1): 44-53.

Allen, L. H., Fox T. R., and Campbell, R. G. 2005. What is ahead for intensive pine plantation silviculture in the South. Southern Journal of Applied Forestry 29(2): 62-69.

Amateis, R. L., and Burkhart, H. E. 2012. Rotation-age results from a loblolly pine spacing trial. Southern Journal of Applied Forestry 36(1): 11-18.

Amateis, R. L., and Burkhart, H. E. 2005. The influence of thinning on the proportion of peeler, sawtimber, and pulpwood trees in loblolly pine plantations. Southern Journal of Applied Forestry 29(3): 158-162.

Amateis, R. L., Radtke, P. J., and Hansen, G. D. 2004. The effect of spacing rectangularity on stem quality in loblolly pine plantations. Canadian Journal of Forest Research 34: 498-501.

Aspinwall, M. J., King, J. S., McKeand, S. E., and Bullock, B. P. 2011. Genetic effects on stand-level uniformity and above and belowground dry mass production in juvenile loblolly pine. Forest Ecology and Management 262: 609-619.

Baldwin Jr, V. C., Peterson, K. D., Clark III, A., Ferguson, R. B., Strub, R. B., and Bower D. R. 2001. The effects of spacing and thinning on stand and tree characteristics of 38-year-old loblolly pine. Forest Ecology and Management 137: 91-102.

Belli, K. L., Land Jr, S. B., and Duzan Jr., H. W. 1997. A tree quality scoring system for immature loblolly pine. Southern Journal of Applied Forestry 21(1): 24-27.

Borders, B. E., and Bailey, R. 2001. Loblolly pine - pushing the limits of growth. Southern Journal of Applied Forestry 25(2): 69-74.

Borders, B., and Volfovicz, R. 2010. Impact of Cultural Treatments and Planting Density on Branch Characteristics of Loblolly Pine At Seven and Eight Years of Age. PMRC Technical Report 2010-2. Plantation Management Research Cooperative, Warnell School of Forestry and Natural Resources, University of Georgia. Athens, GA. 192pp.

Borders, B. E., Will, R. E., Markewitz, D., Clark, A., Hendrick, R., Teskey, R. O., and Zhang, Y. 2004. Effect of complete competition control and annual fertilization on stem growth and canopy relations for a chronosequence of loblolly pine plantations in the Lower Coastal Plain of Georgia. Forest Ecology and Management 192: 21-37.

Burkes, E. C., Will, R. E., Barron-Gafford, G. A., Teskey, R. O., and Shiver, B. 2003. Biomass partitioning and growth efficiency of intensively managed *Pinus taeda* and *Pinus elliottii* stands of different planting densities. Forest Science 49(2): 224-234.

Carlson, C. A., Fox, T. R., Creighton, J., Colbert, S. R., Kelting, D. L., Allen, H. L., and Albaugh, T. J. 2006. Growth and survival of *Pinus taeda* in response to surface and subsurface tillage in the southeastern United States. Forest Ecology and Management 234: 209-217.

Carlson, C. A., Fox, T. R., Creighton, J., Dougherty, P. M., and Johnson, J. R. 2009. Nine-year growth responses to planting density manipulation and repeated early fertilization in a loblolly pine stand in the Virgina Piedmont. Southern Journal of Applied Forestry 33(3): 109-114.

Creighton, J. L., Zutter, B. R., Glover, G. R., and Gjerstad, D. H. 1987. Planted pine growth and survival responses to herbaceous vegetation control, treatment duration, and herbicide application technique. Southern Journal of Applied Forestry 11(4): 223-227.

Cumbie, W. P., Isik, F., and McKeand, S. E. 2012. Genetic improvement of sawtimber potential in loblolly pine. Forest Science 58(2): 168-177.

DeBell, D. S., and Harrington, C. A. 2002. Density and rectangularity of planting influence 20-year growth and development of red alder. Canadian Journal of Forest Research 32: 1244-1253.

Fortson, J. C., and Shiver, B. E., Shackelford, L. 1996. Removal of competing vegetation from established loblolly pine plantations increases growth on Piedmont and Upper Coastal Plain sites. Southern Journal of Applied Forestry 20(4): 188-192.

Fox, T. R., Jokela, E. J., and Allen, H. L. 2004. The evolution of pine plantation silviculture in the southern United States. Gen. Tech. Rep. SRS-75. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. Chapter 8. pp. 63-82.

Gent, J. A., Allen, H. L., Campbell, R. G., and Wells, C. G. 1986. Magnitude, duration, and economic analysis of loblolly pine growth response following bedding and phosphorus fertilization. Southern Journal of Applied Forestry 10: 124-127.

Guldin, J. M., Fitzpatrick, M. W. 1991. Comparison of log quality from even-aged and uneven-aged loblolly pine in south Arkansas. Southern Journal of Applied Forestry 15(1): 10-17.

Harms, W. R., Whitesell, C. D., and DeBell, D. S. 2000. Growth and development of loblolly pine in a spacing trial planted in Hawaii. Forest Ecology and Management 126: 13-24.

Hennessey, T. C., Dougherty, P. M., Lynch, T. B., Wittwer, R. F., and Lorenzi, E. M. 2004. Long-term growth and ecophysiological responses of a southeastern Oklahoma loblolly pine plantation to early rotation thinning. Forest Ecology and Management 192: 97-116.

Ikonen, VP., Kellomaki, S., and Peltola, H. 2009. Sawn timber properties of Scots pine as affected by initial stand density, thinning and pruning: A simulation based approach. Silva Fennica 43(3): 411-431.

Jokela, E. J., Harding, R. B., and Nowak, C. A. 1989. Long-term effects of fertilization on stem form, growth relations, and yield estimates of slash pine. Forest Science 35(3): 832-842.

Jokela, E. J. 2004. Nutrient management of southern pines. Slash pine: Still Growing and Growing! Proceedings of the slash pine symposium. Gen. Tech. Rep. SRS-76. Asheville, NC: U.S. Department of Agriculture, Forest Serivce. Southern Research Station. pp. 27-35.

Jokela, E. J., and Long, A. J. 2000. Using soils to guide fertilizer recommendations for southern pines. Florida Cooperative Extension Service Circular 1230. 11p.

Jokela, E. J., Wilson, D. S., and Allen, J. E. 2000. Early growth responses of slash and loblolly pine following fertilization and herbaceous weed control treatments at establishment. Southern Journal of Applied Forestry 24(1): 23-30.

Jokela, E. J., Dougherty, P. M., and Martin, T. A. 2004. Production dynamics of intensively managed loblolly pine stands in the southern United States: A synthesis of seven long-term experiments. Forest Ecology and Management 192: 117-130.

Kinane, S. M. 2014. Consortium for Accelerated Pine Production Studies (CAPPS). 25 years of Intensive Loblolly Pine Plantation Management. M.S. Thesis, Warnell School of Forestry and Natural Resources. University of Georgia. Athens, GA. 368pp.

MacDonald, E., and Hubert, J. 2002. A review of the effects of silviculture on timber quality of sitka spruce. Forestry 75(2): 107-138.

Malinauskas, A. 1999. The influence of the initial density and site conditions on Scots pine growth and wood quality. Baltic Forestry 5(2): 8-19.

McKeand, S. E., Jokela, E. J., Huber, D. A., Byram, T. D., Allen, H. L., Li, B., and Mullin, T. J. 2006. Performance of improved genotypes of loblolly pine across different soils, climates, and silviculture inputs. Forest Ecology and Management 227: 178-184.

McKeand, S. E., Abt, R. C., Allen, H. L., Li, B., and Catts, G. P. 2006. What are the best loblolly pine genotypes worth to landowners. Journal of Forestry 104(7): 352-358.

McKeand, S. E., Crook, R. P., and Allen, H. L. 1997. Genotypic stability effects on predicted family responses to silvicultural treatments in loblolly pine. Southern Journal of Applied Forestry 21(2): 84-89.

Morris, L. A., and Lowery, R. F. 1988. Influence of site preparation on soil conditions affecting stand establishment and tree growth. Southern Journal of Applied Forestry 12(3): 170-178.

Norman, T. B. 2014. Impacts on growth and quality of interplanting loblolly pine (*Pinus taeda* L.) seedlings with clonal material in the Lower Coastal Plain of North Carolina. M.S. Thesis, North Carolina State University Department of Forestry and Enviromental Resources. Raleigh, NC. 116 pp.

Nyland, R. D. 2002. Silviculture: Concepts and Applications. McGraw-Hill Co., New York. 2ed 94-95, 682 pp.

Oppenheimer, M. J., Shiver, B. D., and Rheney, J. W. 1989. Ten-year growth response of midrotation slash pine plantations to control of competing vegetation. Canadian Journal of Forest Research 19: 329-334.

Pienaar, L. V., and Shiver, B. D. 1984. The effect of planting density on dominant height in unthinned slash pine plantations. Forest Science 30(4): 1059-1066.

Prescher, F., and Stahl, E. G. 1986. The effect of provenance and spacing on stem straightness and number of spike knots of Scots pine in south and central Sweden. Studia Forestalia Suecica: 1-12.

Prestemon, J. P., and Buongiorno, J. 2000. Determinants of tree quality and lumber value in natural uneven-aged southern pine stands. Canadian Journal of Forest Research 30: 211-219.

Quicke, H., Glover, G., and Glover, R. 1999. Loblolly pine growth response to herbaceous vegetation control at different planting densities. Canadian Journal of Forest Research 29: 960-967.

Roth, B. E., Jokela, E. J., Martin, T. A., Huber, D. A., and White, T. L. 2007. Genotype x environment interactions in selected loblolly and slash pine plantations in the southeastern United States. Forest Ecology and Management 238: 175-188.

Shiver, B. 2004. Loblolly versus slash pine growth and yield comparisons. Slash pine: Still Growing and Growing! Proceedings of the slash pine symposium. Gen. Tech. Rep. SRS-76. Asheville, NC: U.S. Department of Agriculture, Forest Service Southern Research Station. 45-49.

Stahl, E. G., Persson, B., and Prescher, F. 1990. Effect of provenance and spacing on stem straightness and number of stems with spike knots in *Pinus sylvestris* L. - Northern Sweden and countrywide models. Studia Forestalia Suecica 184: 1-16.

Subedi, S., Kane, M., Zhao, D., Borders, E., and Greene, D. 2012. Cultural intensity and planting density effects on aboveground biomass of 12-year-old loblolly pine trees in the Upper Coastal Plain and Piedmont of the southeastern United States. Forest Ecology and Management 267: 157-162.

Tang, D., Lenhart, J. D., and Kronrad, G. D. 1992. Development of a provisional tree quality index for planted loblolly pines in east Texas. Southern Journal of Applied Forestry 16: 106-110.

Teglemark, D. O. 1999. Prediction of stem properties based on climate and soil factors in naturally regenerated *Pinus sylvestris* stands. Scandinavian Journal of Forest Research 14: 131-142.

Wang, M., Kane, M., and Zhao, D. 2014. SAGS Culture/Density Study: Age 15 Results. PMRC Technical Report 2014-2. Plantation Management Research Cooperative, Warnell School of Forestry and Natural Resources, University of Georgia. Athens, GA. 82pp.

Ware, L. M., and Stahelin, R. 1948. Growth of southern pine plantations at various spacing. Journal of Forestry 46(4): 267-274.

Wheeler, G. L., Meade, F. M., and Russell, M. W. 1982. Growth of loblolly pine in the Arkansas Ozarks. Southern Journal of Applied Forestry 6(4): 215-217.

Wheeler, G. L., Will, R. E., Markewitz D., Jacobson, M. A., and Shirley, A. M. 2002. Early loblolly pine stand response to tillage on the Piedmont and Upper Coastal Plain of Georgia: Mortality, stand uniformity, and second and third year growth. Southern Journal of Applied Forestry 26(4): 181-189.

Will, R. E., Munger, G. T., Zhang, Y., and Borders, B. E. 2002. Effects of annual fertilization and complete competition control on current annual increment, foliar development, and growth efficiency of different aged *Pinus taeda* stands. Canadian Journal of Forest Research 32: 1728-1740.

Will, R., Hennessey, T., Lynch, T., Holeman, R., and Helnemann, R. 2010. Effects of planting density and seed source on loblolly pine stands in southeastern Oklahoma. Forest Science 56(5): 437-443.

Williston. 1983. Management of shortleaf pine plantations in north Mississippi. Southern Journal of Applied Forestry 7(4): 194-197.

Xiong, J. S., McKeand, S. E., Whetten, R. W., and Isik, F. T. 2014. Genetics of stem forking and ramicorn branches in a cloned loblolly pine family. Forest Science 60(2): 360-366.

Zhao, D., Kane, M., and Borders, B. E. 2010. Development and applications of the relative spacing model for loblolly pine plantations. Forest Ecology and Management 259: 1922-1929.

Zhao, D., Kane, M., and Borders, B. E. 2011. Growth responses to planting density and management intensity in loblolly pine plantations in the southeastern USA Lower Coastal Plain. Annals of Forest Science 68:625-635.

Zhao, D., Kane, M., Borders, B. E., Subedi, S., and Akers, M. 2012. Effects of cultural intensity and planting density on stand-level aboveground biomass production and allocation for 12-year-old loblolly pine plantations in the Upper Coastal Plain and Piedmont of the southeastern United States. Canadian Journal of Forest Research 42: 111-122.

Tables and Figures

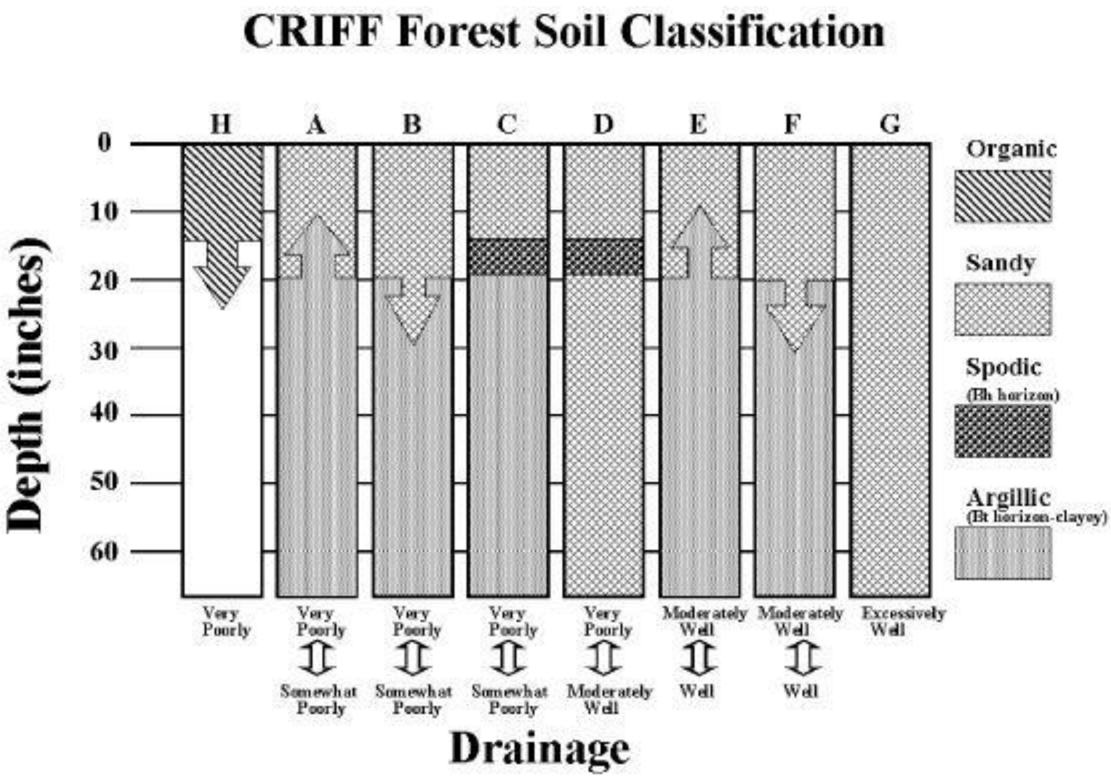

Figure 1.1: CRIFF forest soil classification system.

CHAPTER 2[1]

CULTURE INTENSITY AND STAND DENSITY EFFECTS ON TREE QUALITY IN MIDROTATION NON-THINNED LOBLOLLY PINE PLANTATIONS IN THE SOUTHEAST

[1] Green, P.C., Kane, M., Bullock, B., Daniels, R., Lazar, N. To be submitted to Forest Science.

Abstract

Six non-thinned loblolly pine (*Pinus taeda*) culture x density studies in the Piedmont and Upper Coastal Plain of the Southeast, U.S., the Plantation Management Research Cooperative (PMRC) South Atlantic Gulf Slope (SAGS) studies, were used to examine the effects of two cultural intensities, three planting densities, and their interactions on solid wood potential as well as the proportion and position of product defining defects. Product defining defects are defined as stem defects that limit any solid wood products beyond the location of the defect (e.g. forking, crooks, broken tops). A tree quality index (TQI), was used to grade standing timber for solid wood potential. All product defining defects were measured to the nearest foot. Results show that operational management intensity produced a higher proportion of trees with solid wood product potential than did more intensive management. Operational management exhibited fewer product defining defects. Further, the average product defining defect position was higher on the stem in the operational management regime. While planting density has many significant effects on stand attributes, results show little to no effect on tree quality. Further, planting density appears to have little effect on the proportion and position of product defining defects. These results suggest that management intensity is more important than planting density for the solid wood product potential indicators evaluated.

Introduction

Of all the southern pines, loblolly pine has the largest native range and is the most commonly planted species in the U.S. South (Martin and Shiver 2002). With demands expected to increase globally for wood products, there will be an increased importance on effectively managing loblolly pine (Fox 2000).

Of all the management decisions made for a planted pine stand, the choice of initial planting density is one of the most important decisions a forester must make (Amateis and Burkhart 2012). It is well known that planting density affects a variety of stand attributes. Higher density stands exhibit lower average breast height diameter, higher standing volume, and higher partitioning to stems and branches (Zhao et al. 2012). Studies examining the effects of planting density on average dominant height have shown mixed results. Slash pine grown at various densities in South Africa resulted in no significant differences in dominant height (Pienaar and Shiver 1984) while planted loblolly in southeastern Oklahoma showed deceasing height with increasing density (Hennessey et al. 2004). In a rotation length loblolly pine spacing study in the Virgina and North Carolina Piedmont and Coastal Plain, it was concluded that no single planting density was optimal for every management objective (Amateis and Burkhart 2012).

Plantations growing under non-thinned conditions develop differently than those that receive thinning treatments. Non-thinned stands development is characterized by significantly more natural mortality due to intraspecific competition (Nyland 2002). Development of non-thinned stands is further characterized by smaller average diameters and often little effect on total heights. A thinning study conducted in southeastern Oklahoma found that at age 24 in non-thinned plots, average diameter was significantly lower than for two levels of pre-commercial thinning intensity at age 9 (Hennessey et al. 2004). In this same study, thinning did not significantly affect average total height. While basal area per acre and stem biomass of the thinned stands never reached that of the non-thinned control plot, the basal area and volume was spread across higher value products. Outside of loblolly pine's natural range in the Ozark Mountains in Arkansas, non-thinned plots exhibited less diameter growth while having greater stand volume growth (Wheeler et al. 1982). Non-thinned stands arrive at overstocked conditions earlier compared with thinned stands. Non-thinned plots in a shortleaf pine thinning study in Mississippi demonstrated heavy mortality once the stand reached 135 square feet/acre of basal area at age 28 (Williston 1983). In a region-wide loblolly thinning study, non-thinned plots contained smaller proportions of solid wood products than did the thinned plots (Amateis and Burkhart 2005).

With the great advancements made in the productivity of southern pine, especially loblolly pine, there has been limited research on how silviculture affects the stem quality of individual trees. Many assumptions about the effects of silviculture have been made however quantifying stem quality has 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 (Amateis et al. 2004). A common assumption is that slower grown trees tend to exhibit better stem quality. This assumption is supported by several studies. In uneven-aged southern pine stands, lower productivity sites tended to carry trees with higher stem quality (Prestemon and Buongiorno 2000). The quality of sawn Scots pine in Scandinavia was found inversely related to the radial growth of the stem (Ikonen et al. 2009). In a similar study in Sweden, it was shown that productive soils were found to produce lower quality Scots pine than low productivity soils

(Teglemark 1999). There is no known research on the effect of the combination of stand density and culture on stem quality for southern pine systems.

Limited efforts have been made to model loblolly pine quality. A study of 186 region-wide loblolly samples found that the proportion of peeler logs increased after a thinning, however, the proportion of sawtimber was not significantly changed. Models were developed using diameter at breast height to predict proportion of sawtimber trees (Burkhart and Bredenkamp 1989). Over the first 21 years of the same region-wide loblolly pine study, the probability of a tree obtaining a particular product classification of peeler, sawtimber, or pulpwood was related to its diameter and the number of times that a stand had been thinned. Using this information, proportional odds modeling was used to develop equations to predict product proportions (Amateis and Burkhart 2005). A merchantability model constructed for individual loblolly pine trees found that merchantability was highly correlated with diameter and total height (Strub et al. 1986). There are no known whole stand tree quality models that incorporate stand density and management intensity.

The South Atlantic Gulf Slope (SAGS) culture x density study was installed by the Plantation Management Research Cooperative (PMRC) in 1998 to study the combined effects on loblolly pine stand development with six levels of planting density and two levels of management intensity. The study was establish across a wide geographic range covering the Piedmont and Upper Coastal Plain of the southern United States. This study has provided large amounts of valuable information regarding development of loblolly pine stands. The influence that both management intensity and planting density have on stand development is dramatic (Wang et al. 2104). Lacking in this study are reported results of how the combined effects of planting density and culture intensity effect stem form and the presence and position of product defining defects. 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 or TQI, is a simple, effective method used to operationally grade stems in many operational timber inventories. On any tree with a product defining defect such as a fork or broken tops, the height of defect on the stem was measured and recorded to the nearest foot. This research will better quantify how density and management affect tree quality. Findings will help managers make more informed decisions when establishing loblolly pine plantations in the Southeast.

Hypotheses

1. More intensive management of loblolly pine will decrease overall tree quality in a stand.
2. Within a range of planting densities that have been used for commercial plantations, higher planting density will result in improved stem quality in loblolly pine.
3. Management intensity and planting density will affect the proportion and position of product defining defects in a stand.
4. There will be an interaction of management intensity and planting density in loblolly pine plantations, with better quality with the higher density operational culture combination.

Methods and Materials

Site Description

This research utilized six loblolly pine installations of the South Atlantic Gulf Slope (SAGS) Culture Density study and are all 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 2.1). All installations were on upland, well drained sites common to this region.

Standard tree measurements were taken at age 15 and the tree quality assessments were done during the 16th growing season. Expressed site index ranged from 69 to 89, (Table 2.1), for stands planted at 600 TPA receiving operational culture.

Three of the tested planting densities were evaluated: 300, 600, and 900 trees per acre (TPA). Two management intensities were tested; operational and intensive. The operational treatment consisted of early competition control and several fertilization treatments while the intensive treatment consists of numerous fertilizations and complete competition control throughout the entire rotation (Table 2.2). At each installation, a split-plot design was used. The main plots consisted of the two management intensities while the subplots consisted of the planting densities. Planting on each site occurred in 1998 and seedlings were sourced by the PMRC cooperator in charge of the given installation. At each planting location, seedlings were double planted and were reduced to one seedling after the first growing season. This ensured adequate survival on each installation. Plot size varied by planting density (Table 2.3), and each plot contains a measurement plot surrounded by a buffer approximately 26 feet wide. Age 15 stand attributes by plot are shown in Table 2.4.

Measurements

Diameter at breast height (DBH) was measured on every tree in the measurement plot to the nearest 1/10th of an inch. Total height and height to live crown were measured on every other tree to the nearest foot. Those trees without measured heights were estimated using the following linear regression model: $\ln(H) = \beta_0 + \beta_1(D^{-1})$ with data collected from trees with measured heights.

During the age 16 growing season, additional 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 was measured with a laser hypsometer to the nearest foot. 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 (Table 2.5). A score of 1 indicates that the tree has solid wood product potential and is free of any moderate to major defects including disease, crook, sweep, large knots, forks, or broken tops below 48 feet. Trees with product defining defects or disease above 48 feet can be classified as a TQI 1. A tree assigned a TQI 2 has solid wood potential but has defects that will limit its merchantability. Moderate sweep, crook, disease, and knots are acceptable. Product defining defects are allowed above 16 feet. A tree assigned a TQI 3 has major defects that will eliminate any solid wood product potential. Once classified as a TQI 3, a given tree is assumed to be pulpwood forever. A tree assigned a TQI 4 has major defects such as serious disease, very poor form, or extremely stunted growth, that will preclude any merchantability. This tree is classified as cull. It is important to note that the TQI system scores tree product potential, not necessarily current product. If a defect was present in the lower 10 feet of the tree that did not seriously affect the product potential of the stem, the height of this defect, also known as a jump butt, was measured and recorded. An example of such defect would be a rust gall in the first 2 feet of the stem. Such a defect would commonly be removed in a harvest and the rest of the stem would be merchandized accordingly.

Analysis

All analysis conducted for this research was conducted using the R statistical package (R Core Team 2014). All graphics were developed using the packages ggplot2 (Wickham 2009) and vcd (Meyer et al. 2014).

Analysis of Tree Quality Index Data

With the tree quality index being an ordered categorical response, traditional ANOVA methods are not typically considered appropriate for working with this portion of data analysis. Chi-squared type analysis was used for analyzing this type of categorical data. Mosaic plots were used to graphically represent the deviation of independence when analyze both planting density and management intensity's effects together on tree quality per Simonoff (2003).

The structure of the TQI method lends itself well to a transformation to a binary response. TQI 1 and TQI 2 can be combined to a 1, which is yes the tree has solid wood product potential. TQI 3 and TQI 4 can be combined to a 0, which is the tree does not have solid wood product potential. While this does dilute the data, transforming to a binary format allows for expanded analysis methods. When transformed into the binary format, proportion comparison tests are an appropriate analysis method.

Using ANOVA to analyze categorical data is not usually recommended. While the TQI scores are numeric, they are actually ordinal categorical measurements. With this said, use of an ANOVA to analyze this type of information may be informative. While this should not be seen as a formal analysis, it can be used to reinforce other results. A two-way ANOVA was used to compare "average" TQI scores across management intensity and stand density. The interactions between installation, management, and density were also examined.

Analysis of Product Defining Defects Data

Analysis of product defining defects is considered for both the proportion of stems with these defects as well as the average height at which the defects occur. Being a binary response, the analysis of proportions of stems with product defining defects can be approached through both proportion tests and chi-squared goodness of fit tests. Being a numerical response, the heights of the defects were analyzed through a two-way ANOVA design. In the two-way ANOVA, installation, management intensity, planting density, and their interactions were analyzed. The two-way ANOVA were an unbalanced design due to missing defect height observations in the data. If an individual tree does not have a defect, a value cannot be recorded. Any value entered that is not a defect will incorrectly factor into the average defect height. Because of this limitation, an unbalanced design was employed.

Results

Tree Quality

Management intensity affected the distribution of TQI scores. Intensive management reduced the number of stems that score in the higher quality classes (TQI 1 and 2) compared with the operational management (Figure 2.2). When considered in a binary format, a similar trend was observed. Intensive culture reduced the number of trees that exhibit solid wood product potential (Figure 2.3). These results are statistically significant at $\alpha = 0.05$ level (Table 2.6). Planting density appears to have little influence on the distribution of TQI scores. There was a slight decrease in the proportion of trees with TQI scores of 1 or 2 as density increases at most sites (Figure 2.4). When examined in a binary format the same slight trend was observed when examined as proportions of trees with or without solid wood product potential (Figure 2.5). The differences in proportions among planting densities were not significant at $\alpha = 0.05$ level (Table 2.7). The distribution of TQI scores across all sites, are shown for both management intensities in Figure 2.6 and across planting density in Figure 2.7. When analyzed together, the use of a mosaic plot effectively shows the influence of planting density and management intensity on the distribution of TQI scores (Figure 2.8) and the proportions of trees with solid wood potential (Figure 2.9).

While not recommended for categorical data analysis, the results of the two-way ANOVA on the “average” TQI for each density and management combination reinforce previously mentioned results for the study. Results indicate that intensive management decreased overall tree quality. This result is significant at the alpha=0.05 level. Further, results also indicate that planting density did not significantly affect tree quality in a stand (Table 2.8).

Product Defining Defects

The effects of management intensity and planting density were examined for both the proportion of trees that exhibit product defining defects as well as the average height at which the defects occur. Management intensity affected both the proportion of stems with the defects present as well as the average height at which the defects occur. Intensive management increased the frequency of the product defining defects across sites (Figure 2.10). When viewed across installation, the proportion of stems with product defining defects was higher in intensive management (Figure 2.11). Intensive management lowered the average height of the defects across sites (Figure 2.12). When viewed by installation, the average height of the product defining defects was lower for intensive management (Figure 2.13). The difference in proportions of product defining defect heights between management intensity across all sites was significant at $\alpha=0.05$ (Table 2.9).

The planting densities examined in this study do not appear to have a significant effect on the proportion of product defining defects by installation (Figure 2.14). When viewed across all installations, the 300 tree per acre density exhibited the most trees with product defining defects (Figure 2.15). Product defining defect position varied greatly by installation (Figure 2.16). When averaged across installation, the average height of product defining defects had a slight trend upward as density increases (Figure 2.17). The results of the hypothesis test suggest a difference in proportion of product defining defects between planting densities across all installations (Table 2.10). Two-way ANOVA test results show that average defect height was statistically different at $\alpha = 0.05$ level between the intensive and operation management intensities (Table 2.11). The ANOVA results further show that average defect height was not statistically different at $\alpha = 0.05$ level between the three planting densities of 300, 600 and 900 trees per acre and the interaction of management and planting density was not significant for product defining defects (Table 2.11).

When the operational management is analyzed apart from the intense culture, planted trees per acre again displayed little trend in proportion of product defining defects among installations (Figure 2.18). When analyzed across installations, there is little difference in proportion between densities (Figure 2.19). There was little trend in product defining defect height by planting density at the installation level(Figure 2.20). When analyzed by installation, the product defining defect height slightly increased as density increased (Figure 2.21). While there are minor visual trends, ANOVA testing results indicate no significant differences in average defect height among planting densities (Table 2.12). The proportions of defects among the densities were not significantly different at $\alpha = 0.05$ level (Table 2.13).

Discussion

Tree Quality

Tree quality was significantly influenced by management intensity. Intensive management resulted in fewer trees with solid wood product potential than did the operational intensity. This result is not surprising as several published studies have shown that slower growing trees produces higher quality saw logs (Ikonen et al. 2009). The lack of influence that planting density has shown on tree quality is quite surprising. Even when the operational management is analyzed alone, tree quality as assessed in this study was not significantly influenced by initial density. This result is contrary to common silviculture wisdom of the effects of planting density on overall tree quality. It is important to note that this is a point in time measurement. If observations were made over time, it is possible that significant differences would become apparent. While assessing differences in tree quality among a variety of site productivity levels was not an objective of this study, it has been noted that lower productivity sites exhibit higher quality saw logs compared to sites exhibiting more rapid growth (Stahl et al. 1990). Differences in tree quality due to differing growth rates over a range of geographic locations can be related to various levels of management intensity in similar base growing conditions and regions. Higher management intensity increases tree growth rates as does improving growing conditions due to better sites. With the results of the current study on how more rapid growth rates affect stem quality due to either management or geographic region, more informed management decisions can be made when managing for higher valued solid wood products. If intensive management results in significant growth increases at a large expense of overall tree quality, the additional investment for the increased growth may result in a lower net present value for the rotation due to a reduction of stem quality.

Product Defining Defects

Both the position and proportion of product defining defects were significantly influenced by management intensity. Intensive management resulted in a higher proportion of stems with the defects that on average, occurred lower on the stem. While this result is not surprising, there is no known published research to help explain the reason for these differences. It is possible that intensive management provides the necessary resources to encourage multiple dominant leaders that lead to forking. Further, it is possible that rapid growth encourages crooks, and weakened wood that breaks easily leading to broken tops. Planting density had little influence on the proportion and position of the defects. When planting density was analyzed with only operational management, similar results were found. Planting density appears to have less influence on product defining defects than management intensity.

Product defining defects are a significant driver for overall tree quality and the presence of a defect should be taken into consideration when planning to harvest a tree. Some defects reduce the economic value of a tree very little. A broken top at the top of a mature tree is insignificant compared with multiple dominant leaders that begin low on a stem. While both are product defining defects, the severity of the defect should always be considered. As these studies mature, more product defining defects may appear in certain combinations of management and density. Further measurements will need to be made in the future to confirm these results. Site differences in both the position of the defects and the proportion of stems with product defining defects were significant. This is not surprising because as with tree quality, site influences a variety of tree properties.

Physiological reasons for these effects can only be speculated in this study. It is possible that increased nutrients lead to poor wood quality which in turn increase the chances for broken tops. The increased nutrients could possibly lead to multiple leaders competing for apical dominance thus leading to forking. Stems with greater amounts of nutrients must compete quickly with other stems for available nutrients and sunlight. This could possibly lead to stems that are not as well formed as stems that are not competing as aggressively for available light and nutrients. Genetics were chosen by individual cooperator at each location and thus genetic differences at each site could explain large amounts of the variation in the proportion and position of the product defining defects.

The TQI assessment method chosen to evaluate tree quality was selected because it is a common method to grade standing trees in operational timber inventories. While the hypothesis that the TQI method is a consistent, easy to learn, and effective method for grading standing trees is supported, it is of the opinion of the author that more information should have been collected to supplement the TQI quality assessments. Recording the reason for each assessment would have provided valuable information at the expense of time. An example would be a tree downgraded from a TQI 1 to 2 because of branching. Further, if quality assessments could be independently audited, a level of rigor could be added to the results presented. The SAGS study utilized was selected because of its large geographic range, the experimental design, and the amount of legacy data available. If time were available, more sites in different regions would be assessed. Similar studies exist in the Lower Coastal Plain and Western Gulf regions of the southern United States. A larger number of installations would have possibly provided the ability to develop predictive models to help describe overall stand tree quality with some basic stand attributes as inputs.

Conclusions

The results of this study support the hypothesis that intensive management influences tree quality and product defining defects. Intensive management decreased tree quality while also increasing the proportion of trees with product defining defects and lowering the average product defining defect position. When managing for solid wood products, culture intensity should be considered to produce higher value through a combination of productivity and product quality. Intensive management has the potential to enhance growth rates but also decrease the volume of solid wood products available in a stand.

The results of this study do not support the hypothesis that planting density effects product potential and product defining defects. This result is surprising as it is commonly assumed that planting density is a significant driver on tree quality. This study only examines three planting densities at one point in time. Tree quality is not a static measurement as both climatic and biological changes can influence stems at future times in a stand age. If repeated measurements become available as the stands continue to mature, significant effects of planting density on TQI scores, proportion and position of product defining defects may become apparent. The hypothesis that there was an interaction between planting density and management intensity was not supported.

In conclusion, the results of this study show that management intensity influences tree quality and product defining defects more so than planting density. Using this information, along with known stand effects of management and density affects, should provide managers with the ability to maximize value in managed loblolly pine in the Southeast.

Literature Cited

Amateis, R. L., and Burkhart, H. E. 2005. The influence of thinning on the proportion of peeler, sawtimber, an d pulpwood trees in loblolly pine plantations. Southern Journal of Applied Forestry 29(3): 158-162.

Amateis, R. L., and Burkhart, H. E. 2012. Rotation-age results from a loblolly pine spacing trial. Southern Journal of Applied Forestry 36(1): 11-18.

Amateis, R. L., Radtke, P. J., and Hansen, G. D. 2004. The effect of spacing rectangularity on stem quality in loblolly pine plantations. Canadian Journal of Forest Research 34: 498-501.

Burkhart, H. E., and Bredenkamp, B. V. 1989. Product-class proportions for thinned and unthinned loblolly pine plantations. Southern Journal of Applied Forestry 13: 192-195.

Fox, T. R. 2000. Sustained productivity in intensively managed forest plantations. Forest Ecology and Management 138: 187-202.

Hennessey, T. C., Dougherty, P. M., Lynch, T. B., Wittwer, R. F., and Lorenzi, E. M. 2004. Long-term growth and ecophysiological responses of a southeastern Oklahoma loblolly pine plantation to early rotation thinning. Forest Ecology and Management 192: 97-116.

Ikonen, V., Kellomaki, S., and Peltola, H. 2009. Sawn timber properties of Scots pine as affected by initial stand density, thinning and pruning: A simulation based approach. Silva Fennica 43(3): 411-431.

Martin, S. W., and Shiver, B. D. 2002. Impacts of vegetation control, genetic improvement and their Interaction on loblolly pine growth in the southern United States - age 12 results. Southern Journal of Applied Forestry 26(1): 37-42.

Meyer, D., Zeileis, A., and Hornik, K. 2014. vcd: Visualizing Categorical Data. R package version 1.3-2.

Nyland, R. D. 2002. Silviculture: Concepts and Applications. McGraw-Hill Co., New York. 2ed. 407-428. 682 pp.

Pienaar, L. V., and Shiver, B. D. 1984. The effect of planting density on dominant height in unthinned slash pine plantations. Forest Science 30(4): 1059-1066.

Prestemon, J. P., and Buongiorno, J. 2000. Determinants of tree quality and lumber value in natural uneven-aged southern pine stands. Canadian Journal of Forest Research 30: 211-219.

R Core Team (2014). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Simonoff, J.S. 2003. Analyzing Categorical Data. Springer, New York. 213p.

Stahl, E. G., Persson, B., and Prescher, F. 1990. Effect of provenance and spacing on stem straightness and number of stems with spike knots in *Pinus sylvestris* L. - Northern Sweden and countrywide models. Studia Forestalia Suecica 184: 1-16.

Strub, M. R., Green, E. J., Burkhart, H. E., and Pirie, W. R. 1986. Merchantability of loblolly pine - an application of nonlinear regression with a discrete dependent variable. Forest Science 32(1): 254-261.

Teglemark, D. O. 1999. Prediction of stem properties based on climate and soil factors in naturally regenerated Pinus sylvestris stands. Scandinavian Journal of Forest Research 14: 131-142.

Wang, M., Kane, M., and Zhao, D. 2014. SAGS Culture/Density Study: Age 15 Results. PMRC Technical Report 2014-2. Plantation Management Research Cooperative, Warnell School of Forestry and Natural Resources, University of Georgia. Athens, GA. 82pp.

Wheeler, G. L., Meade, F. M., and Russell, M. W. 1982. Growth of loblolly pine in the Arkansas Ozarks. Southern Journal of Applied Forestry 6(4): 215-217.

Wickham, H. 2009. ggplot2: Elegant graphics for data analysis. Springer, New York.

Williston, H.L,. 1983. Management of shortleaf pine plantations in south Mississippi. Southern Journal of Applied Forestry 7(4): 194-197.

Zhao, D., Kane, M., Borders, B., Subedi, S., and Akers, M. 2012. Effects of cultural intensity and planting density on stand-level aboveground biomass production and allocation for 12-year-old loblolly pine plantations in the Upper Coastal Plain and Piedmont of the southeastern United States. Canadian Journal of Forest Research 42: 111-122.

Tables and Figures

Table 2.1: Geographic details, soil details, and site quality for PMRC SAGS Culture x Density non-thinned installation utilized.

Installation	County	State	Physiographic Province	NRCS Soil Series	Soil Taxonomy	Site Index*
5	Talbot	GA	Piedmont	Lloyd	Fine, kaolinitic, thermic Rhodic Kanhapludults	89
6	Marion	GA	Upper Coastal Plain	Lakeland	Thermic, coated Typic Quartzipsamments	69
13	Jasper	GA	Piedmont	Lloyd - Pacolet	Fine, kaolinitic, thermic Rhodic Kanhapludults	84
16	St. Clair	AL	Piedmont	Conasauga and Firestone	Very-fine, mixed, active, thermic Chromic Vertic Hapludalfs	71
17	Harolson	GA	Piedmont	Grover	Fine-loamy, micaceous, thermic Typic Hapludults	84
18	Chatooga	GA	Piedmont	Fullerton	Fine, smectitic, thermic Vertic Paleudalfs	75

*Site index is shown for operational culture planted at 600 tree per acre base age 25.

Table 2.2: Detail of cultural regimes utilized in PMRC SAGS Culture x 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: 500 lbs/ac 10-10-10 Before year 8: 200 lbs/ac N + 25 lbs/ac P Before year 12: 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 Before year 10: 200 lbs/ac N + 25 lbs/ac P Before year 12: 200 lbs/ac N + 25 lbs/ac P Before year 14: 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

Table 2.3: Planting density plot sizes for PMRC SAGS Culture x Density study.

Planting Density (TPA)	Spacing (ft. x ft.)	Trees per measure plot	Measure plot size (ac)	Gross plot size (ac)
1800	6 x 4	184	0.1	0.31
1500	6 x 4.8	160	0.11	0.32
1200	6 x 6	120	0.1	0.3
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

Table 2.4: Stand attributes of non-thinned PMRC SAGS Culture x Density stands at age 15 by management intensity and initial planting density.

INST	MAN	PLTPA	TPA	MDBH	MHT	MCRWNRAT	HD	TVOB	GWOB	BA	SDI
5	Intensive	300	277	10.9	68.1	0.48	69.0	5308	151	181	320
5	Intensive	600	515	8.6	63.0	0.33	64.7	6064	167	214	415
5	Intensive	900	455	8.4	67.1	0.33	69.3	5437	151	179	350
5	Operational	300	288	10.1	66.9	0.40	68.9	4794	135	164	298
5	Operational	600	546	8.1	63.3	0.32	65.0	5732	157	199	396
5	Operational	900	773	6.8	61.4	0.34	64.4	5804	155	201	428
6	Intensive	300	277	9.8	56.8	0.44	58.5	3761	104	150	275
6	Intensive	600	538	6.5	44.1	0.41	47.8	2965	77	135	289
6	Intensive	900	800	5.9	44.3	0.35	46.9	3405	87	156	352
6	Operational	300	304	7.6	45.6	0.44	49.0	2116	56	99	201
6	Operational	600	531	6.4	44.9	0.45	46.8	2655	68	122	267
6	Operational	900	791	5.2	38.7	0.37	42.3	2391	59	121	285
13	Intensive	300	269	10.8	60.9	0.50	61.7	4571	128	174	308
13	Intensive	600	577	8.3	61.8	0.38	63.2	6096	166	218	430
13	Intensive	900	727	7.2	60.5	0.33	61.9	5896	158	210	437
13	Operational	300	296	9.7	58.1	0.48	58.9	3967	109	155	287
13	Operational	600	577	7.9	58.9	0.41	60.8	5424	147	201	403
13	Operational	900	764	6.9	55.7	0.31	56.9	5340	142	204	432
16	Intensive	300	312	10.4	57.9	0.37	59.7	4695	130	185	334
16	Intensive	600	608	7.8	54.5	0.45	56.7	5187	139	206	415
16	Intensive	900	818	6.9	54.1	0.33	57.2	5695	151	224	471
16	Operational	300	296	9.1	51.3	0.52	53.8	3142	85	136	258
16	Operational	600	615	7.3	47.6	0.43	49.2	3990	104	179	372
16	Operational	900	827	6.8	51.5	0.34	54.4	5231	138	213	454
17	Intensive	300	288	10.8	60.8	0.41	62.1	4891	137	186	330
17	Intensive	600	577	8.5	61.4	0.38	62.5	6376	174	231	451
17	Intensive	900	782	7.3	62.3	0.32	63.8	6655	179	231	479
17	Operational	300	296	10.6	59.4	0.41	60.2	4701	131	182	326
17	Operational	600	585	8.0	59.1	0.38	60.7	5682	154	211	421
17	Operational	900	800	7.1	59.1	0.33	61.1	6210	166	226	472
18	Intensive	300	300	10.3	52.1	0.47	52.6	4022	110	176	318
18	Intensive	600	592	8.3	57.5	0.33	58.1	5867	159	225	444
18	Intensive	900	755	6.9	53.5	0.31	55.2	5053	133	201	425
18	Operational	300	258	10.5	51.3	0.42	52.5	3480	95	155	279
18	Operational	600	523	8.3	52.1	0.36	52.3	4674	125	199	392
18	Operational	900	673	7.3	51.7	0.33	52.7	4825	128	201	416

INST=Installation. **MAN** = Management intensity. **PLTPA** = Planted trees per acre. **TPA** = Current trees per acre. **MDBH** = Average Diameter at Breast Height (inches). **MHT** = Average height (feet). **MCRWNRAT** = Average crown ratio. **HD** = Average dominant height (feet).**TVOB** = Volume outside bark (ft^3). **GWOB** = Green weight outside bark (tons). **BA** = Basal area per acre (ft^2). **SDI** = Stand density index

Table 2.5: Tree Quality Index (TQI), specifications utilized for grading standing trees in the PMRC SAGS Culture x Density study.

TQI Class	Specifications
1	No defects that would limit any solid wood potential. No product defining defects below 48 feet.
2	Moderate defects that will limit solid wood potential. No product defining defects below 16 feet.
3	Major defects that eliminate solid wood potential. Pulpwood forever.
4	Serious defects that eliminate all merchantability. Cull.

Table 2.6: Two-sample test for equality of proportion of stems with solid wood product potential for two levels of management across all installations in PMRC SAGS Culture x Density non-thinned sites.

2-sample test for equality of proportions	
Chi-squared = 65.096, df = 1, p-value < 0.0001	
prop 1 (int. man.)	prop 2 (op. man.)
0.79	0.9

Table 2.7: Three-sample test for equality of proportions of stems without solid wood potential between three levels of planting density for PMRC SAGS Culture x Density non-thinned sites.

3-sample test for equality of proportions without continuity correction		
Chi-squared = 5.57, df = 2, p-value = 0.062		
prop 1 (300 tpa.)	prop 2 (600 tpa.)	prop 3 (900 tpa.)
0.137	0.144	0.174

Table 2.8: Two-way ANOVA for TQI values with test for interaction between PTPA and management for PMRC SAGS Culture x Density non-thinned sites.

	DF	Sum Sq	Mean Sq	F Value	P Value
Installation	5	77.7	15.53	35.56	< 0.0001
PTPA	2	0.9	0.46	1.04	0.352
Man	1	53.9	53.87	123.3	< 0.0001
PTPA:Man	2	2.1	1.04	2.38	0.0929
Residuals	2647	1156.5	0.44		

PTPA = Planted Trees per Acre
Man = Management Intensity

Table 2.9: Two-sample proportion test for proportion of stems without product defining defects between two levels of management intensity for PMRC Culture x Density SAGS non-thinned sites.

2-sample test for equality of proportions	
Chi-squared = 4.9071, df = 1, p-value = 0.02675	
Prop 1 (Int. Man.)	Prop 2 (Op. Man.)
0.79	0.83

Table 2.10: Three-sample proportion test for proportion of stems without product defining defects between three planting densities for PMRC SAGS Culture x Density non-thinned sites.

3-sample test for equality of proportions		
Chi-squared = 7.5294, df = 2, p-value = 0.02317		
prop 1 (300 tpa.)	prop 2 (600 tpa.)	prop 3 (900 tpa.)
0.78	0.82	0.83

Table 2.11: Two-way ANOVA test results for product defining defect heights for PMRC SAGS Culture x Density non-thinned sites.

	DF	Sum Sq	Mean Sq	F Value	P Value
Installation	5	3968	793.5	10.27	< 0.0001
PTPA	2	267	133.3	1.73	0.179
Man	1	612	611.9	7.92	0.005
PTPA:Man	2	91	45.3	0.59	0.557
Residuals	493	38104	77.3		

PTPA = Planted Trees per Acre
Man = Management Intensity

Table 2.12: ANOVA test results for product defining defect heights for planting density, operational management only, for PMRC SAGS Culture x Density non-thinned sites.

	DF	Sum Sq	Mean Sq	F Value	P Value
Installation	5	893	178.5	2.374	0.040
PTPA	2	261	130.5	1.736	0.179
Site:PTPA	9	647	71.8	0.955	0.478
Residuals	218	16393	75.2		

PTPA = Planted Trees per Acre
Man = Management Intensity

Table 2.13: Proportion of stems without product defining defects across planting densities for operational management only for PMRC SAGS Culture x Density non-thinned sites.

3-sample test for equality of proportions without continuity correction		
Chi-squared = 1.39, df = 2, p-value = 0.499		
prop 1 (300 tpa.)	prop 2 (600 tpa.)	prop 3 (900 tpa.)
0.81	0.83	0.84

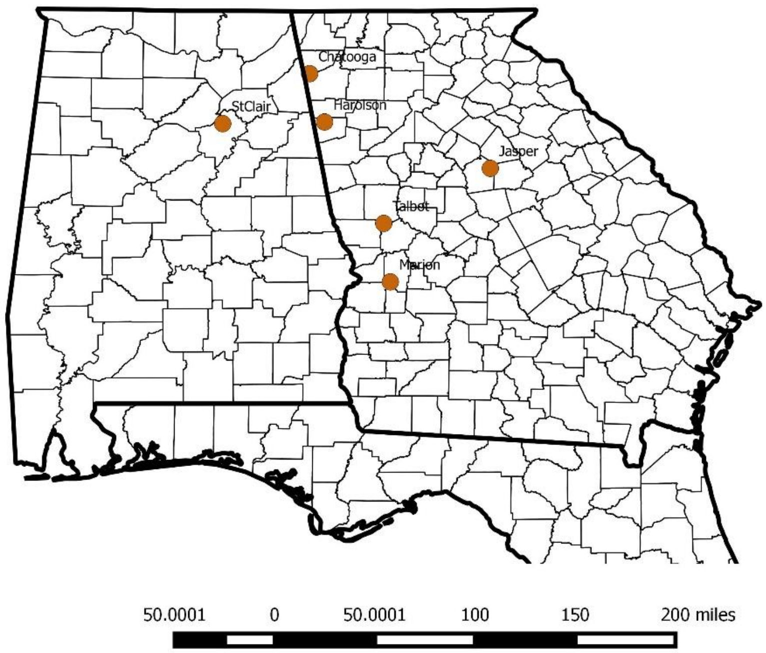

Figure 2.1: Location of Non-thinned PMRC SAGS Culture x Density installations.

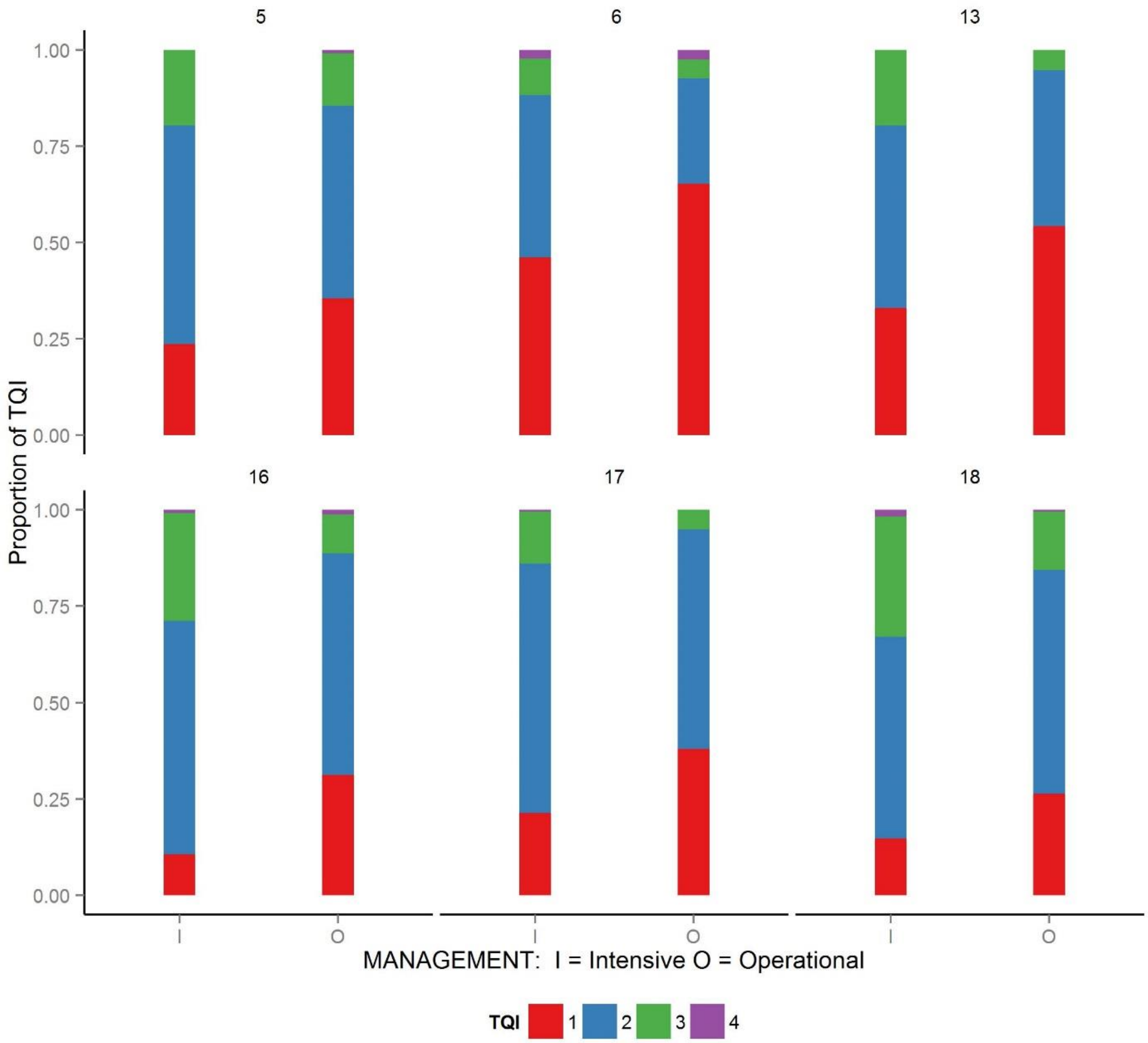

Figure 2.2: Proportion of TQI scores by management intensity and installation for PMRC SAGS Culture x Density non-thinned sites.

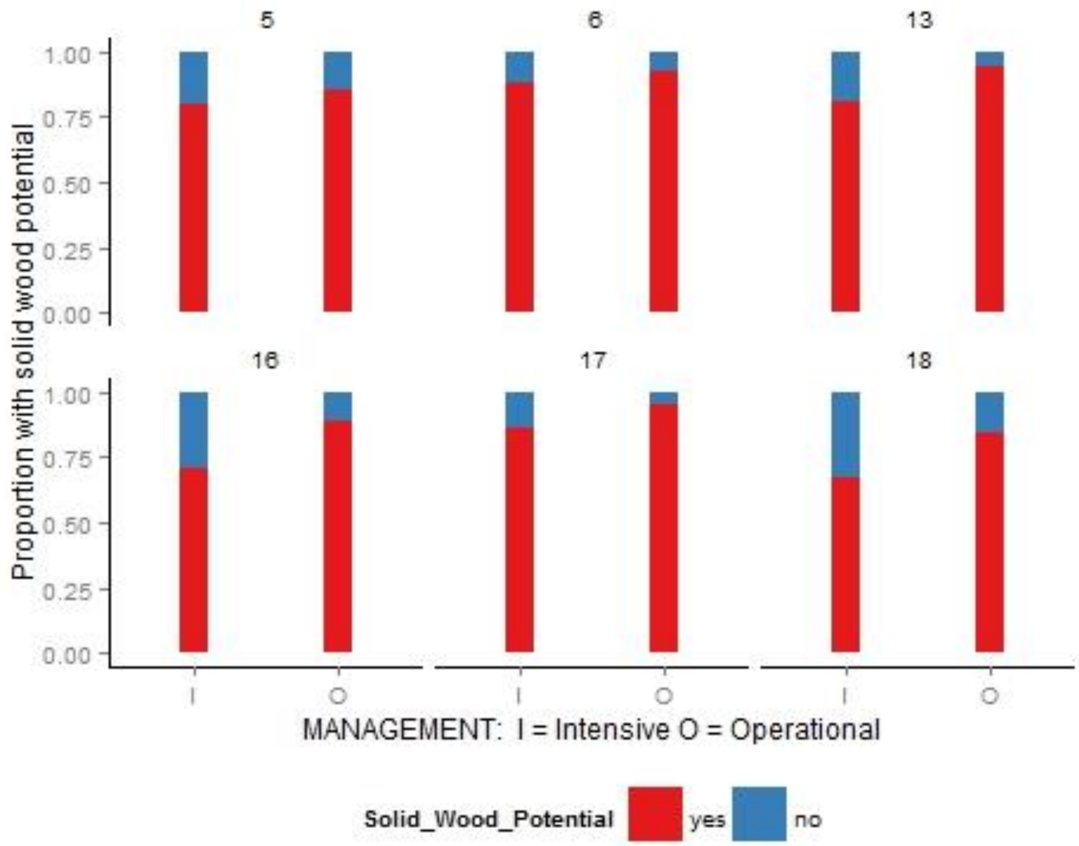

Figure 2.3: Proportion of trees with solid wood product potential by management intensity and installation for PMRC SAGS Culture x Density non-thinned sites.

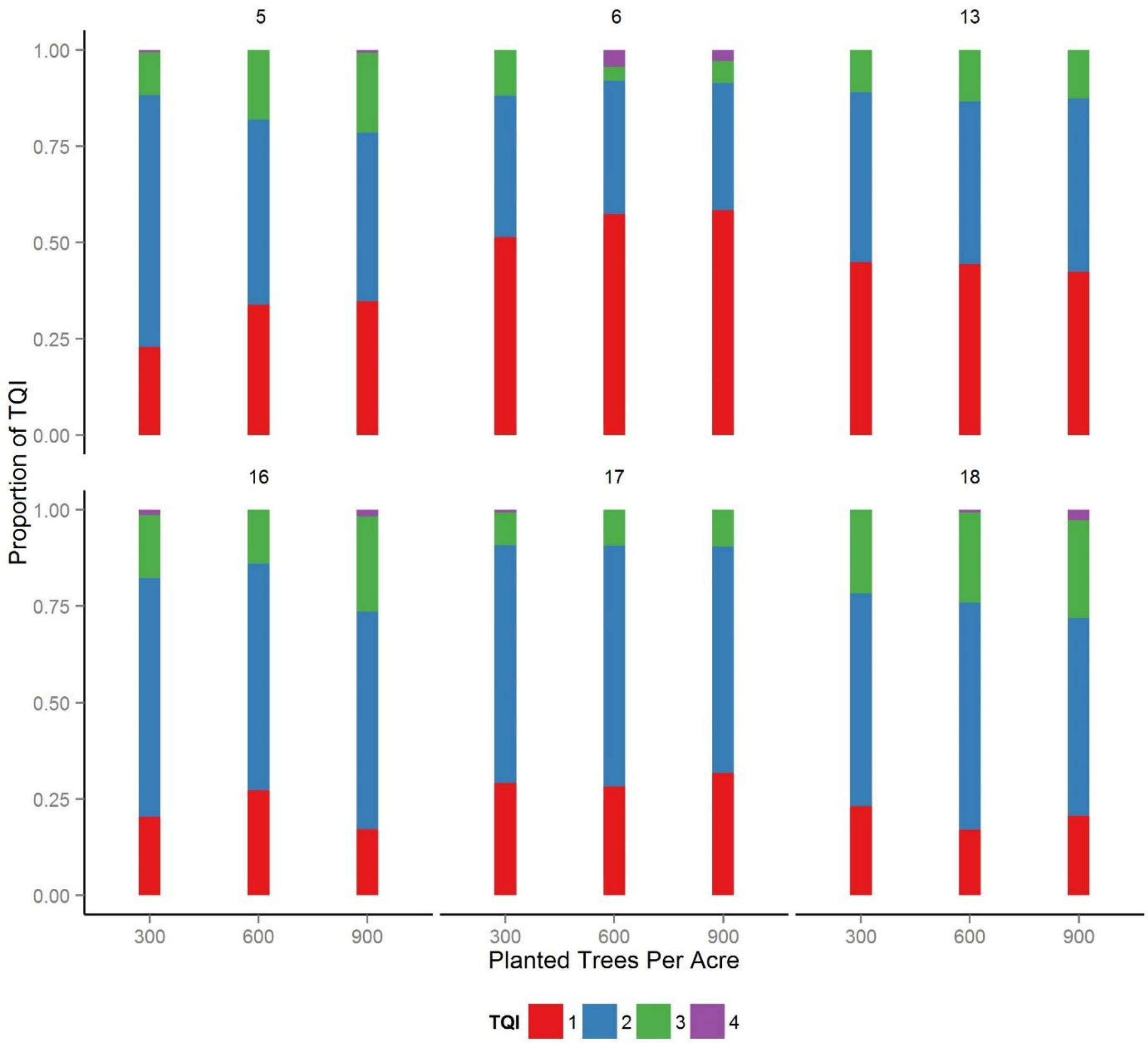

Figure 2.4: Proportion of TQI scores by planted trees per acre and installation for PMRC SAGS Culture x Density non-thinned sites.

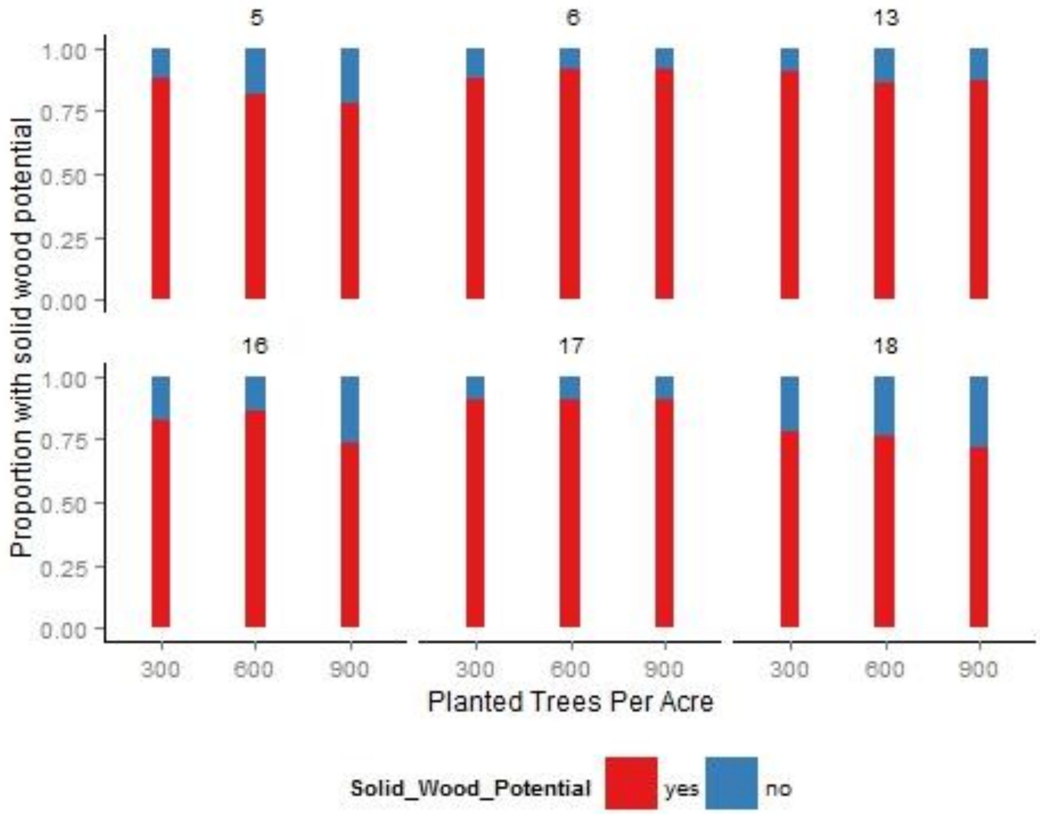

Figure 2.5: Proportion of trees with solid wood potential by planting density and installation for PMRC SAGS Culture x Density non-thinned sites.

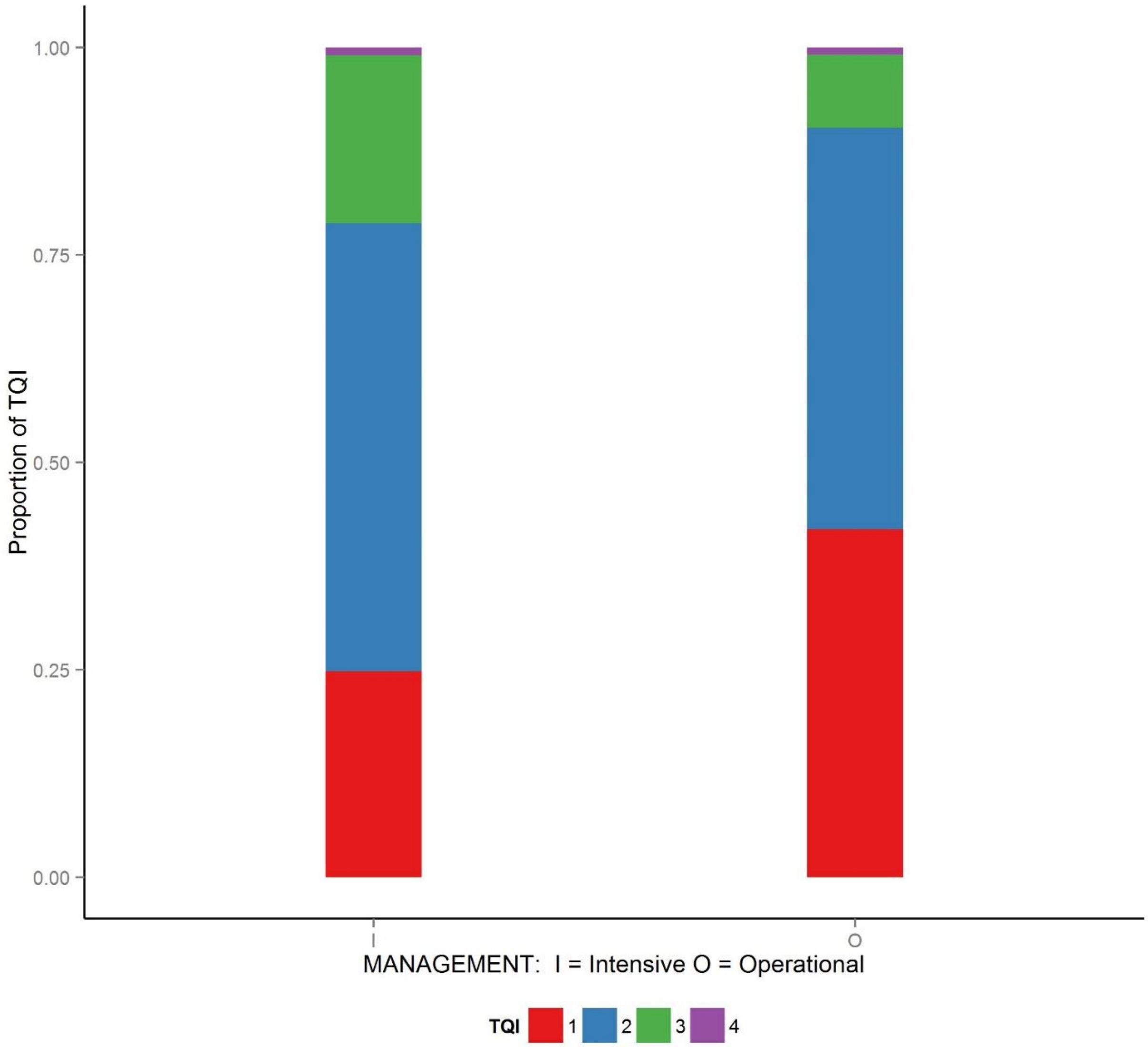

Figure 2.6: Proportion of TQI scores by management intensity across all installations for PMRC SAGS Culture x Density non-thinned sites.

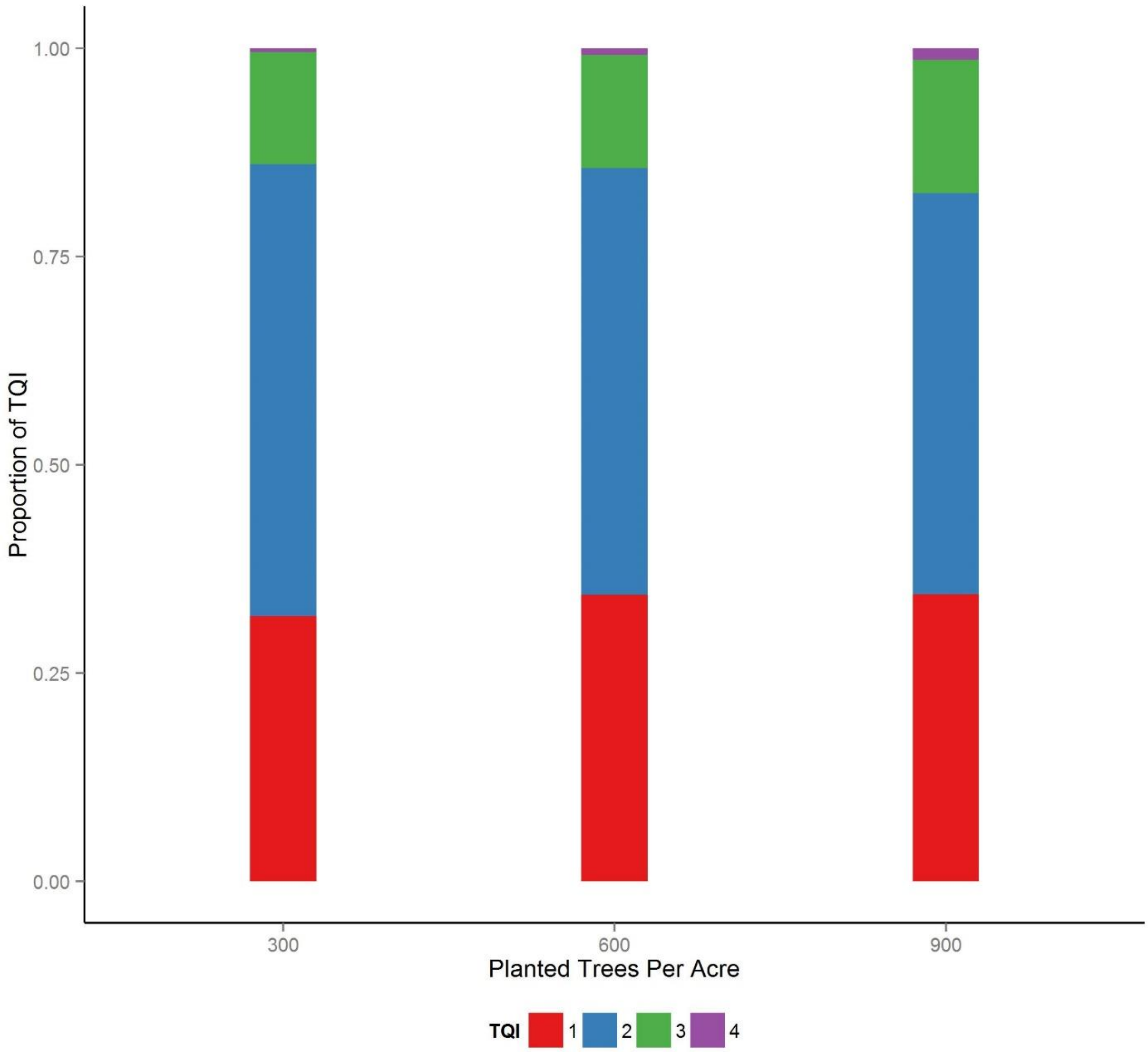

Figure 2.7: Proportion of TQI scores by three planting densities across all installations for PMRC SAGS Culture x Density non-thinned sites.

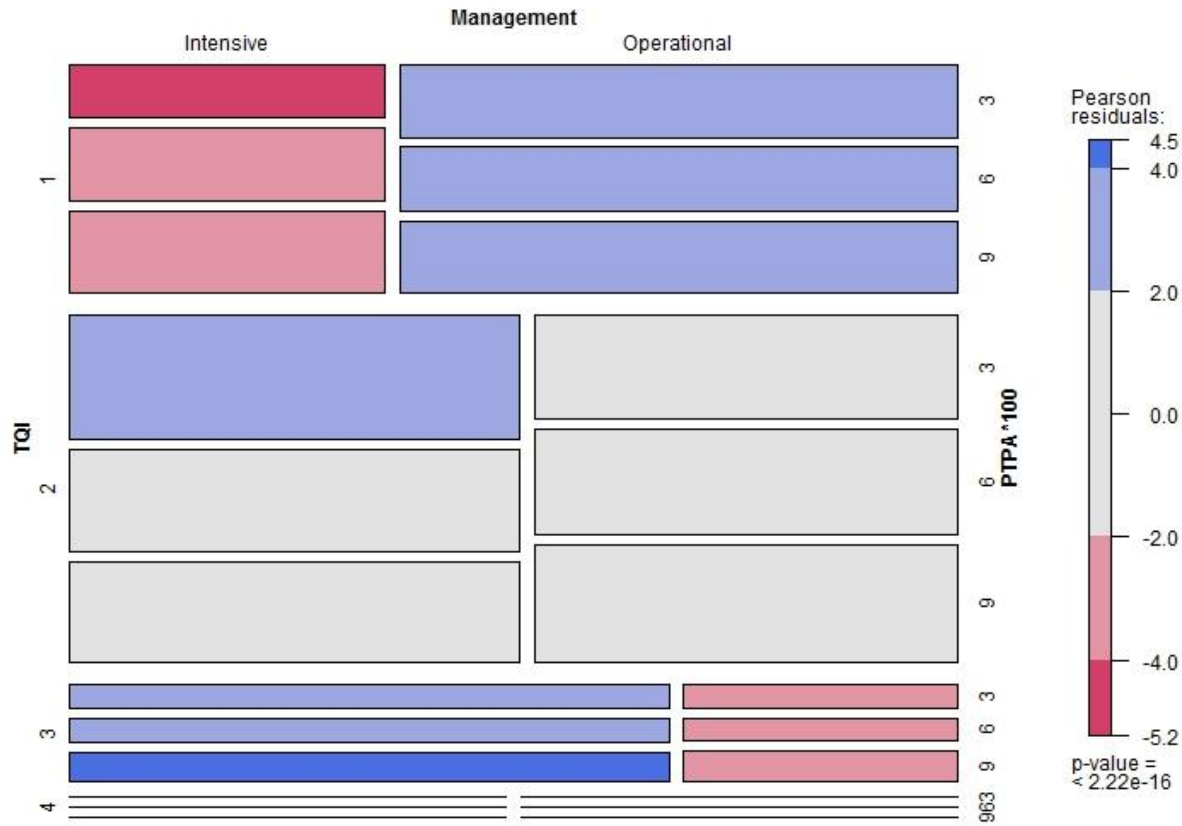

Figure 2.8: Comparison of trees across TQI scores for PMRC SAGS Culture x Density non-thinned installations. The height of the bars refers to planting density. The width of the bars refers to management intensity. The levels of the bars refer to the different TQI scores. When comparing density, the bars are similar in height, the densities are not significantly different. When comparing management, the bars are different in width, the management intensities are significantly different. The Pearson residuals refer to how significantly combinations of management intensity and planting density differ from expected counts of trees.

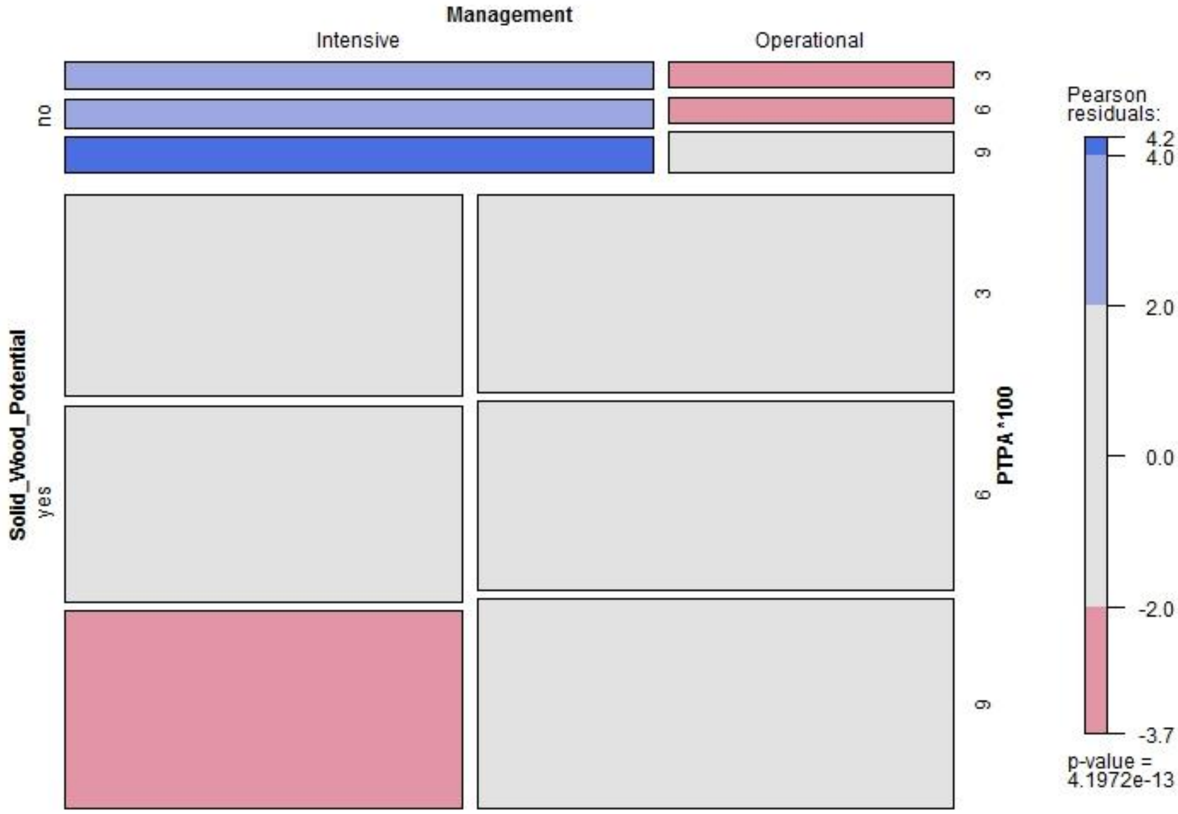

Figure 2.9: Comparison of trees with solid wood product potential for PMRC SAGS Culture x Density non-thinned installations. The height of the bars refers to planting density. The width of the bars refers to management intensity. The first level of bars are trees that do not exhibit solid wood potential while the lower bars are trees that do have solid wood potential. When comparing density, the bars are similar in height, the densities are not significantly different. When comparing management, the bars are different in width, the management intensities are significantly different. The Pearson residuals refer to how significantly combinations of management intensity and planting density differ from expected counts of trees.

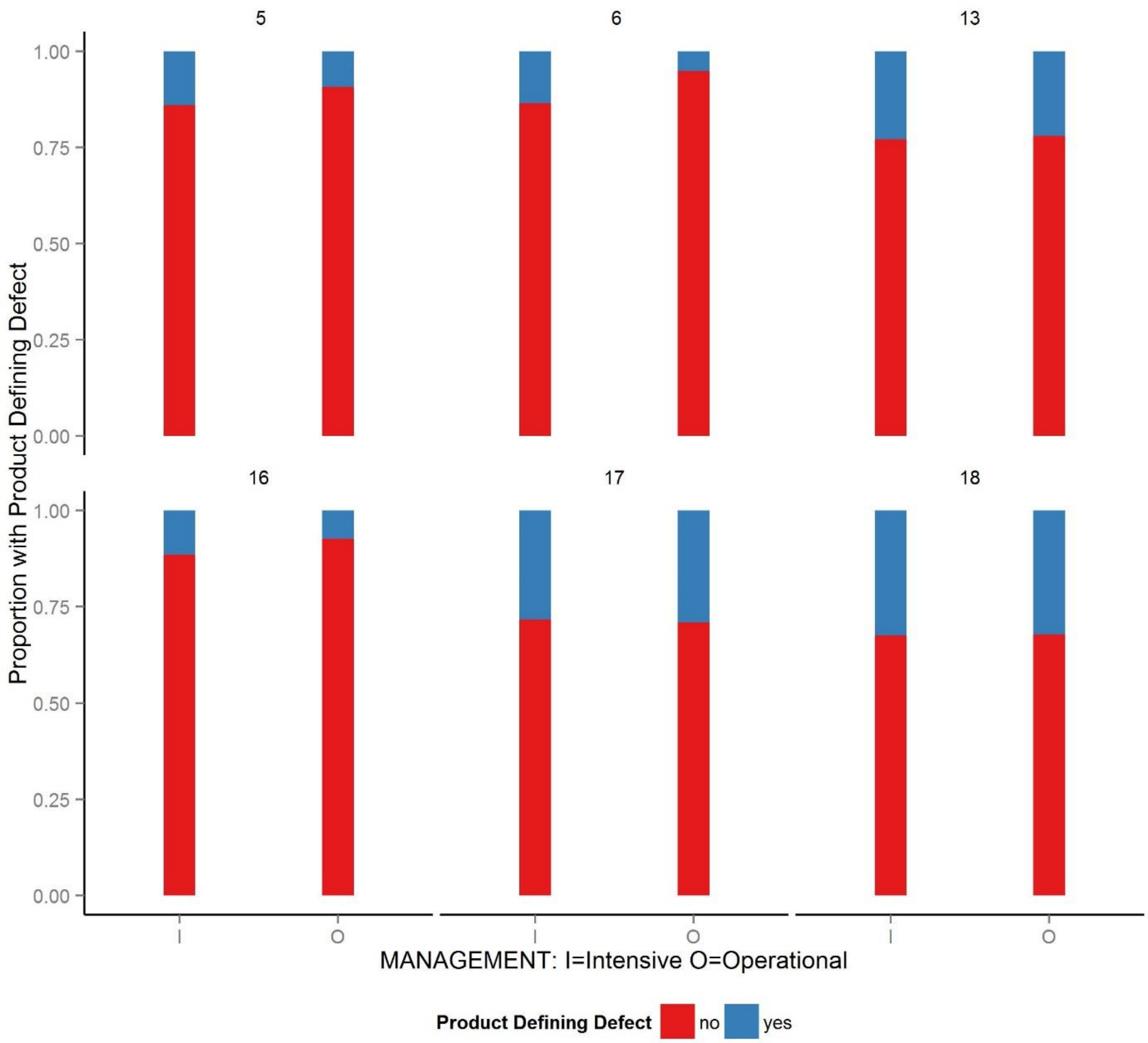

Figure 2.10: Proportion of trees with product defining defects by management intensity and installation for PMRC SAGS Culture x Density non-thinned sites.

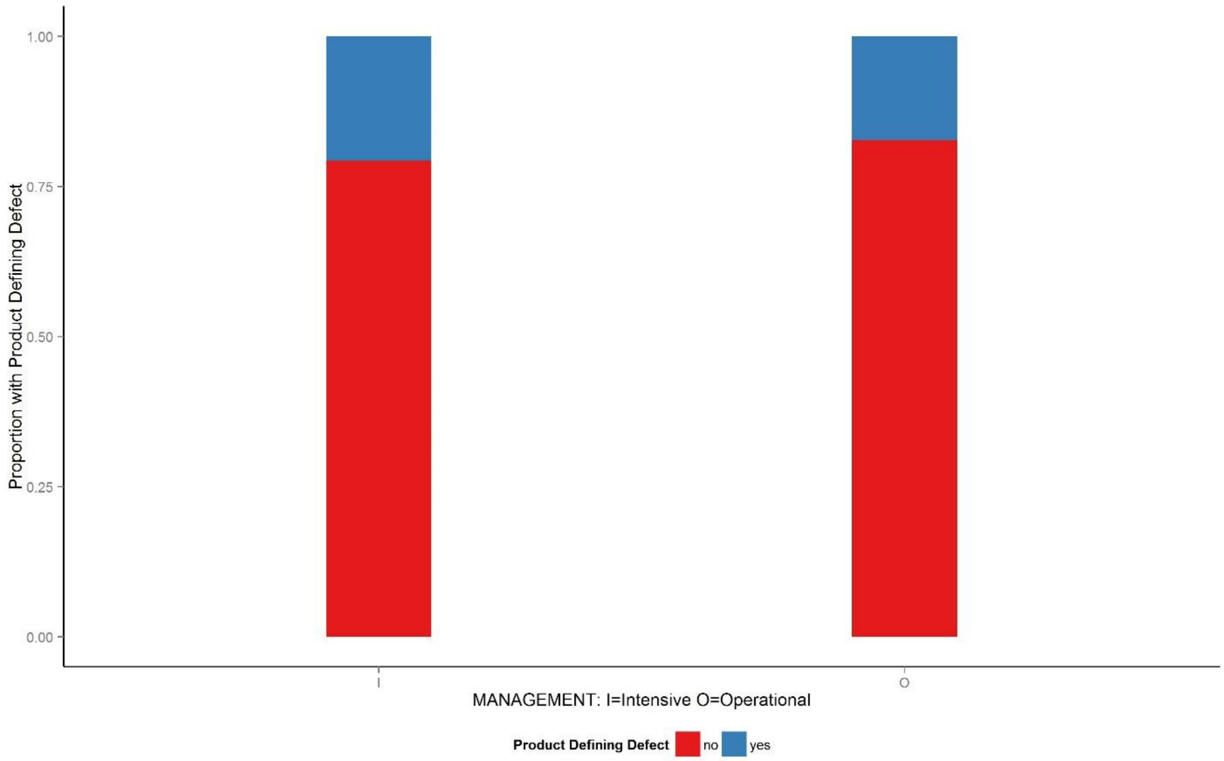

Figure 2.11: Product defining defect proportion by management intensity across all installations for PMRC SAGS Culture x Density non-thinned sites.

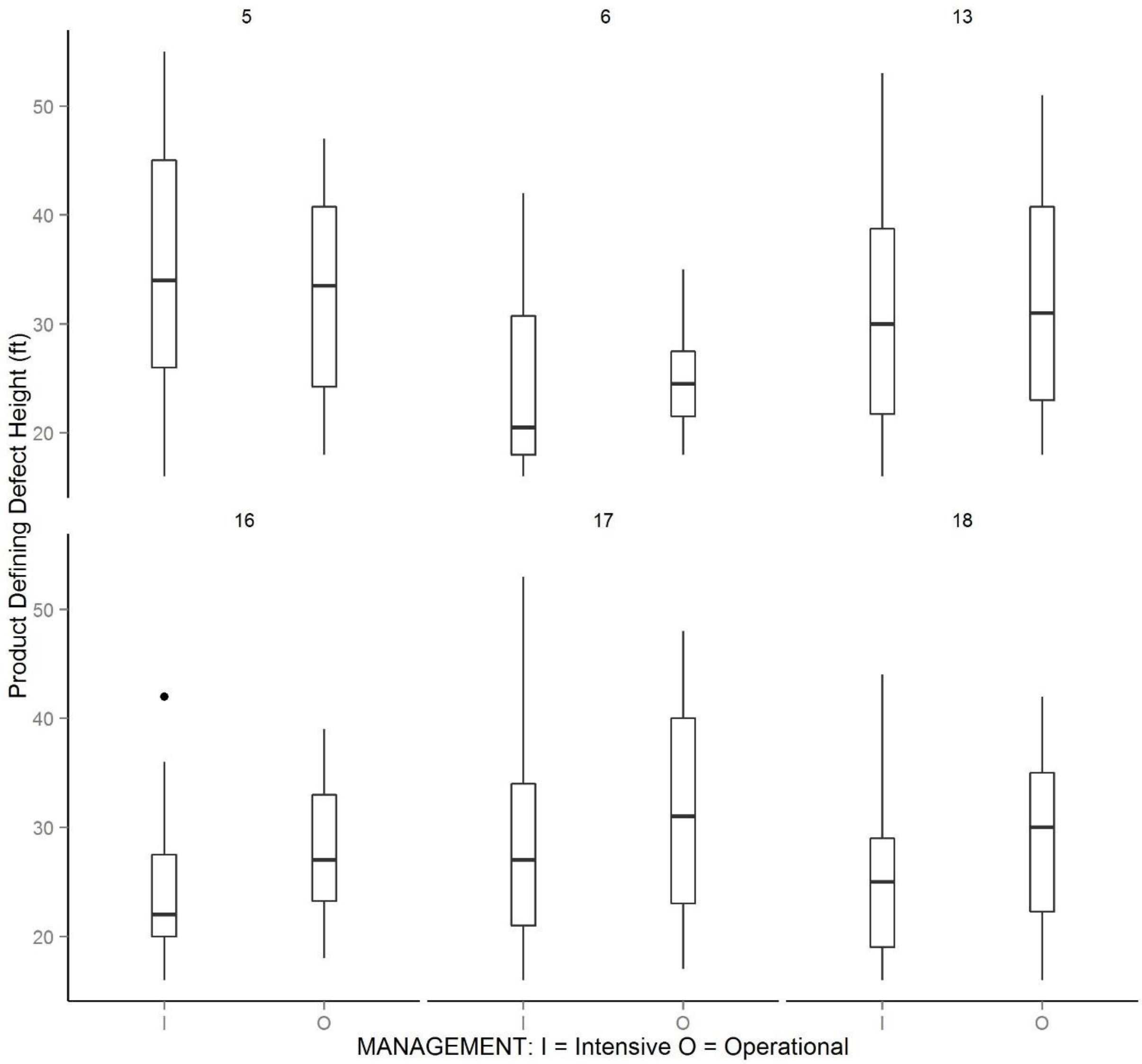

Figure 2.12: Product defining defect heights by management intensity and installation for PMRC SAGS Culture x Density non-thinned sites.

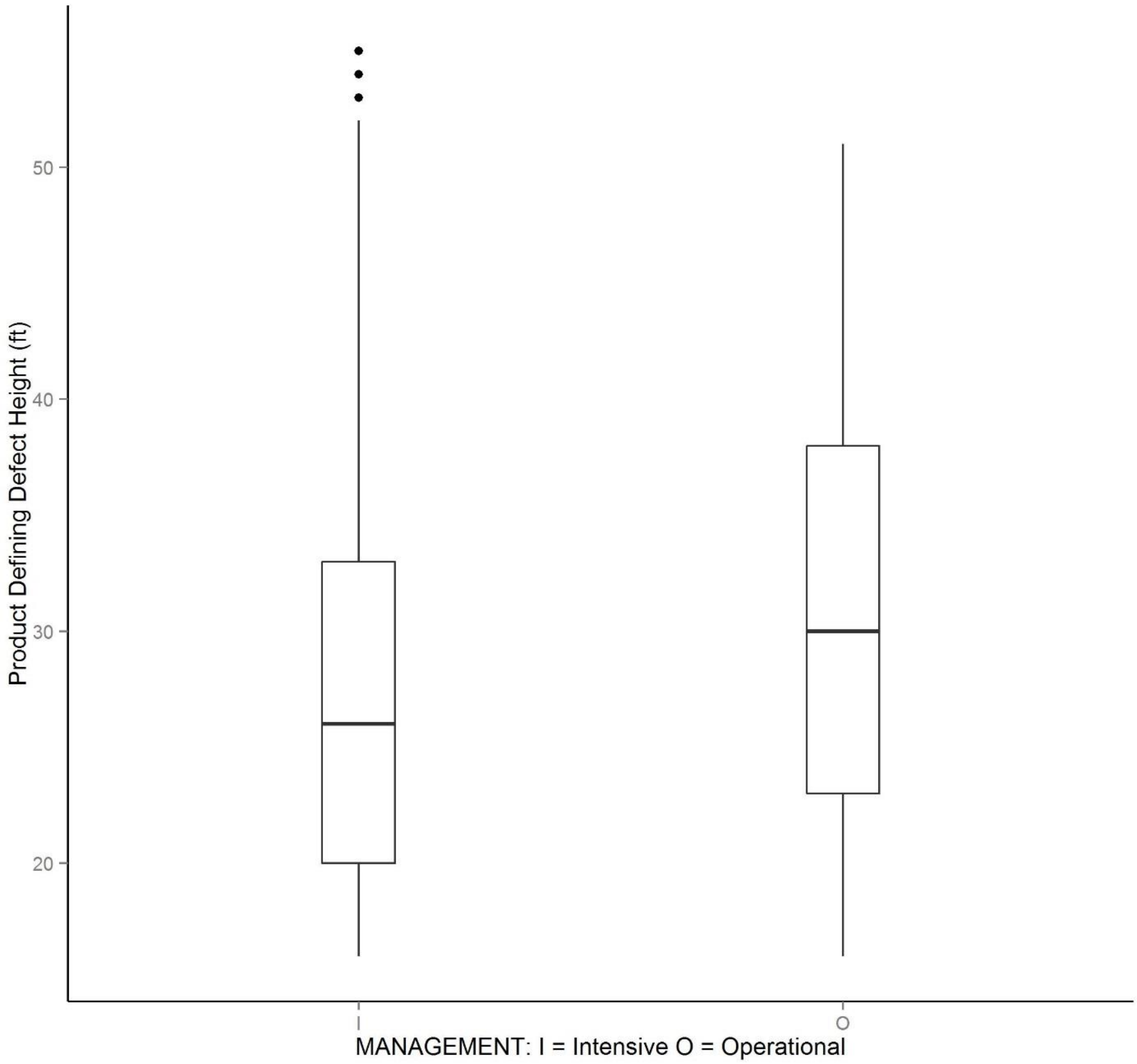

Figure 2.13: Product defining defect position by management intensity across all sites for PMRC SAGS Culture x Density non-thinned sites.

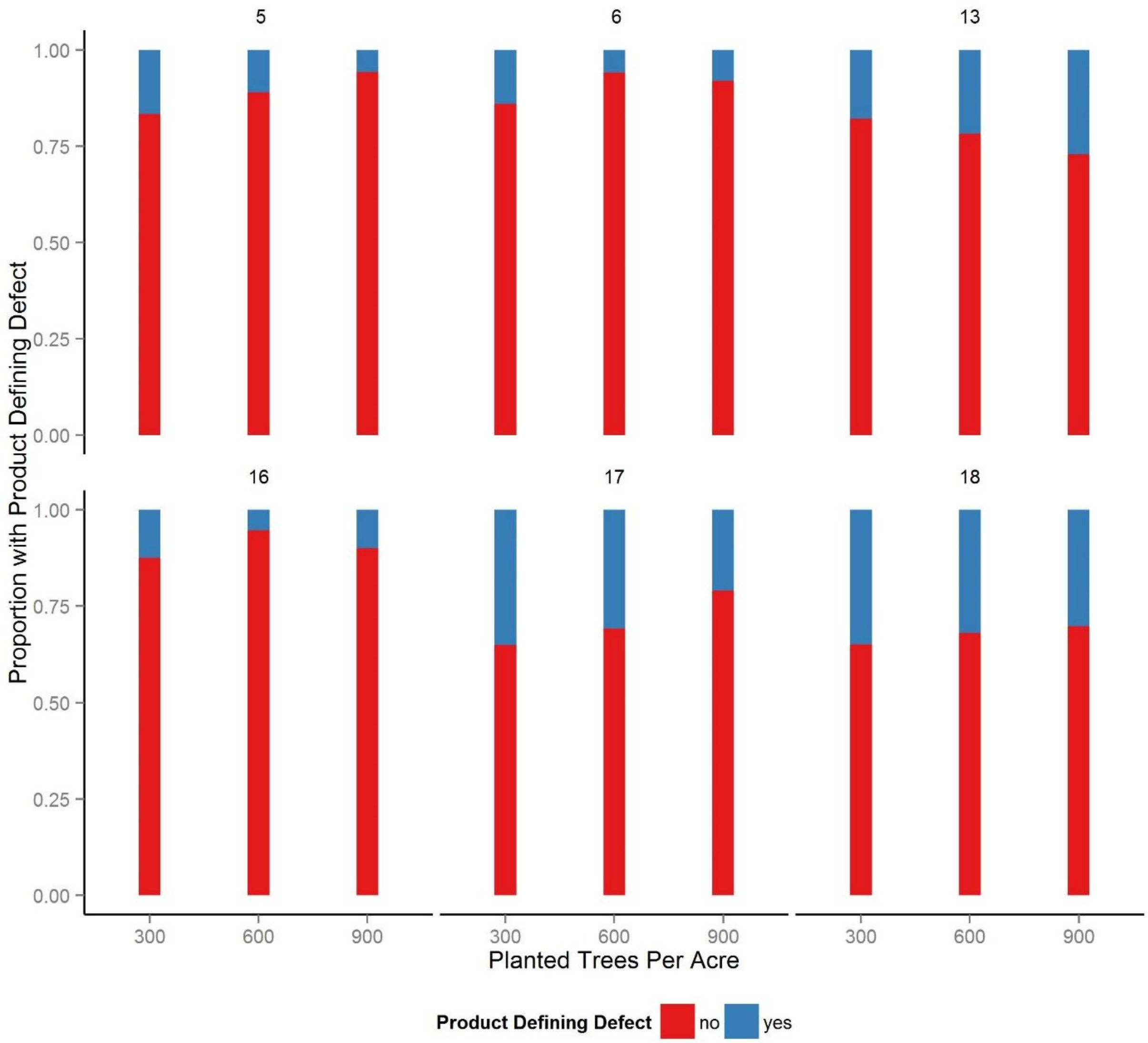

Figure 2.14: Proportion of trees with product defining defects by planted trees per acre and installation for PMRC SAGS Culture x Density non-thinned sites.

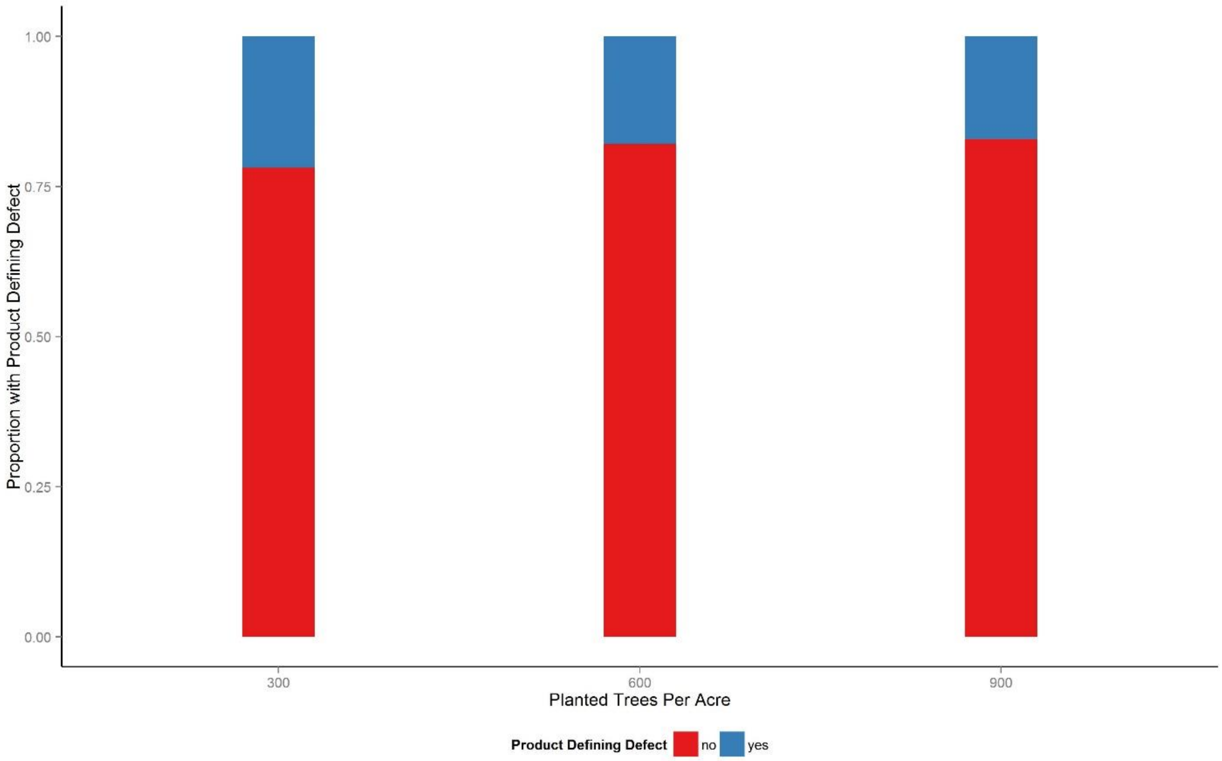

Figure 2.15: Proportion of stems with product defining defects by planting density across all installations for PMRC SAGS Culture x Density non-thinned sites.

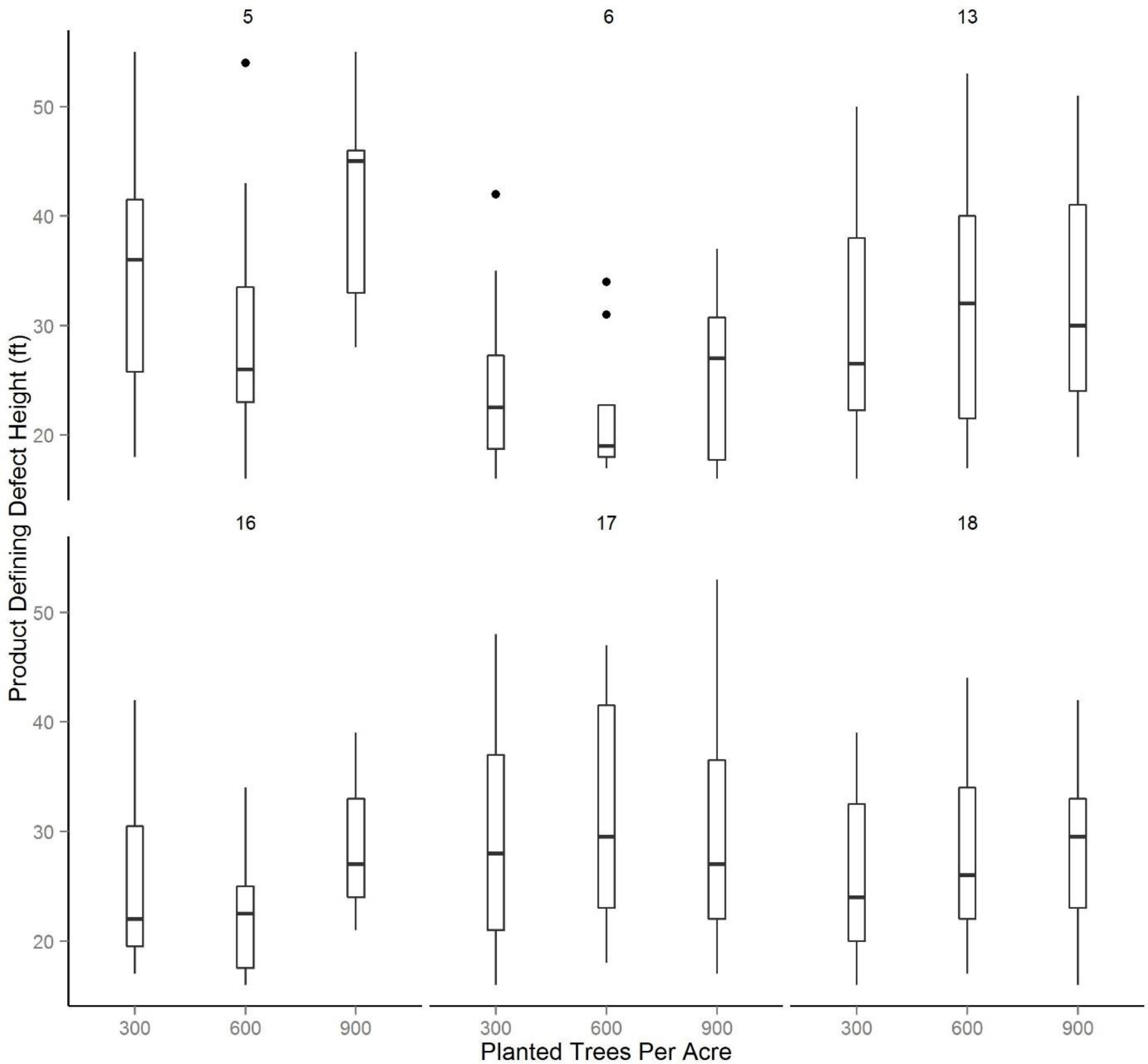

Figure 2.16: Product defining defect heights by planted trees per acre and installation for PMRC SAGS Culture x Density non-thinned sites.

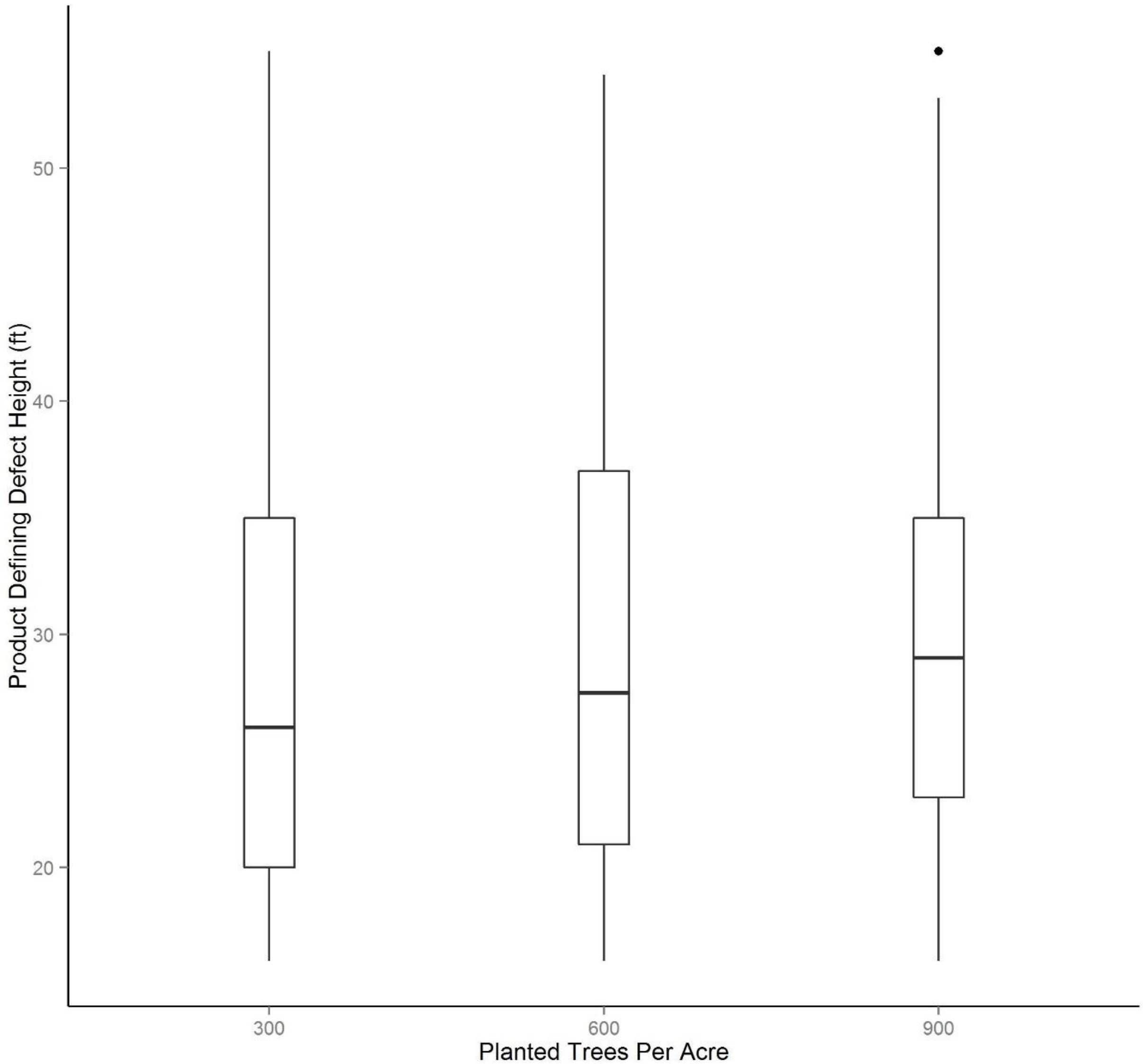

Figure 2.17: Product defining defect height by planting density across all installations for PMRC SAGS Culture x Density non-thinned sites.

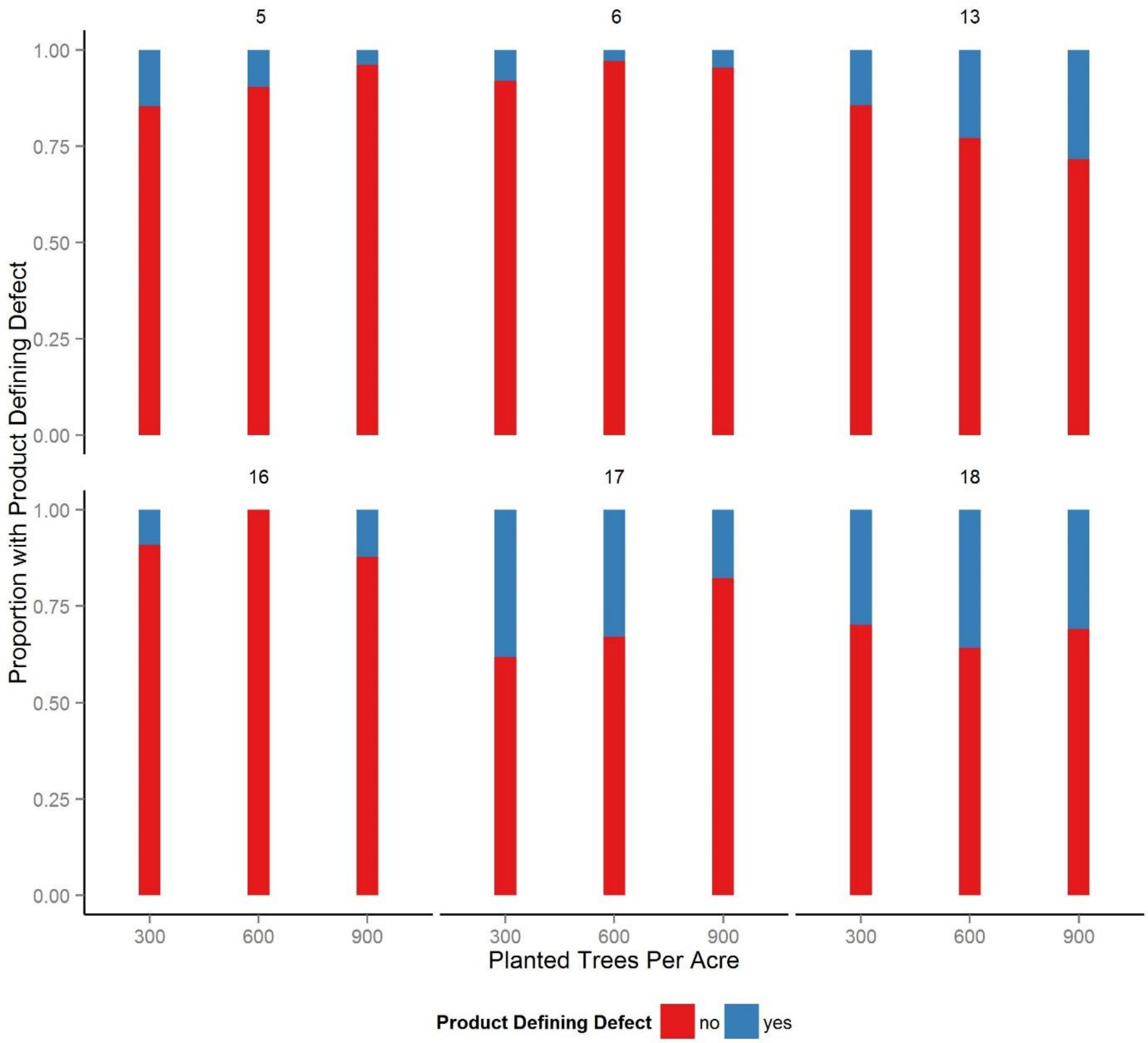

Figure 2.18: Proportion of stems with product defining defects by planted trees per acre and installation (operational management only) for PMRC SAGS Culture x Density non-thinned sites.

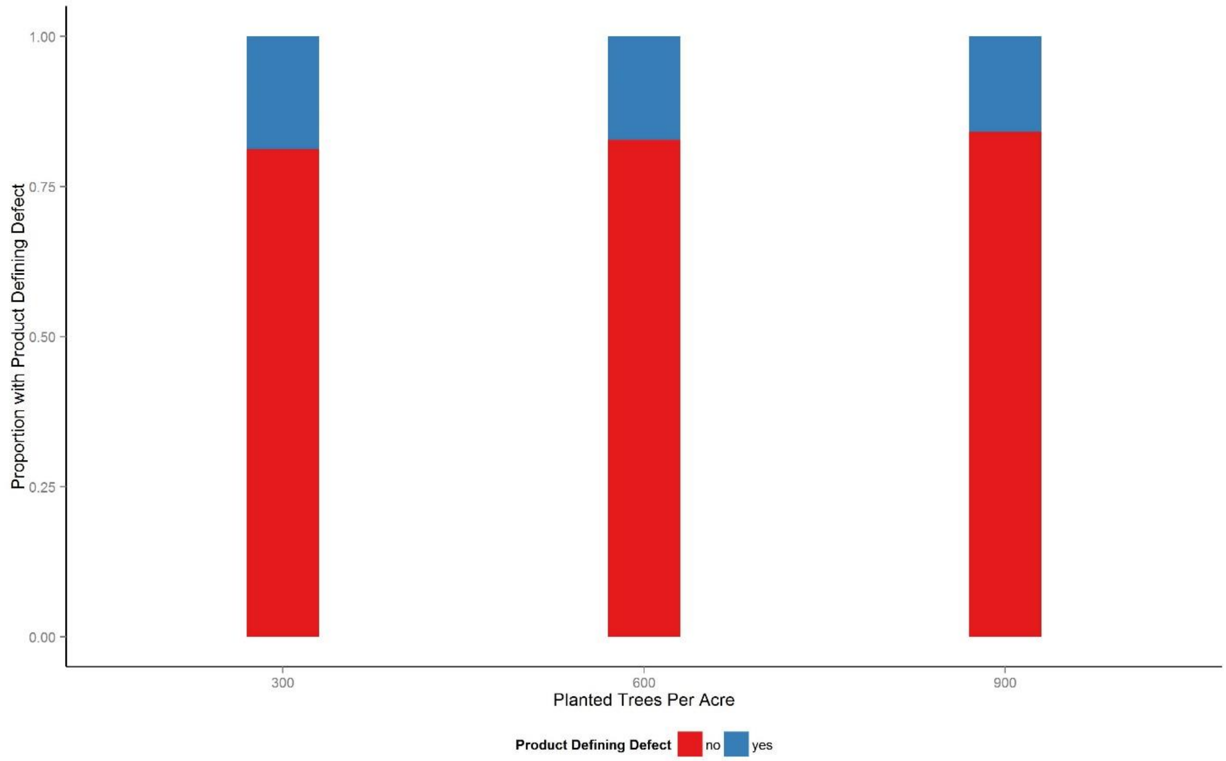

Figure 2.19: Proportion of product defining defects by planted trees per acre operational management only across all installations for PMRC SAGS Culture x Density non-thinned sites.

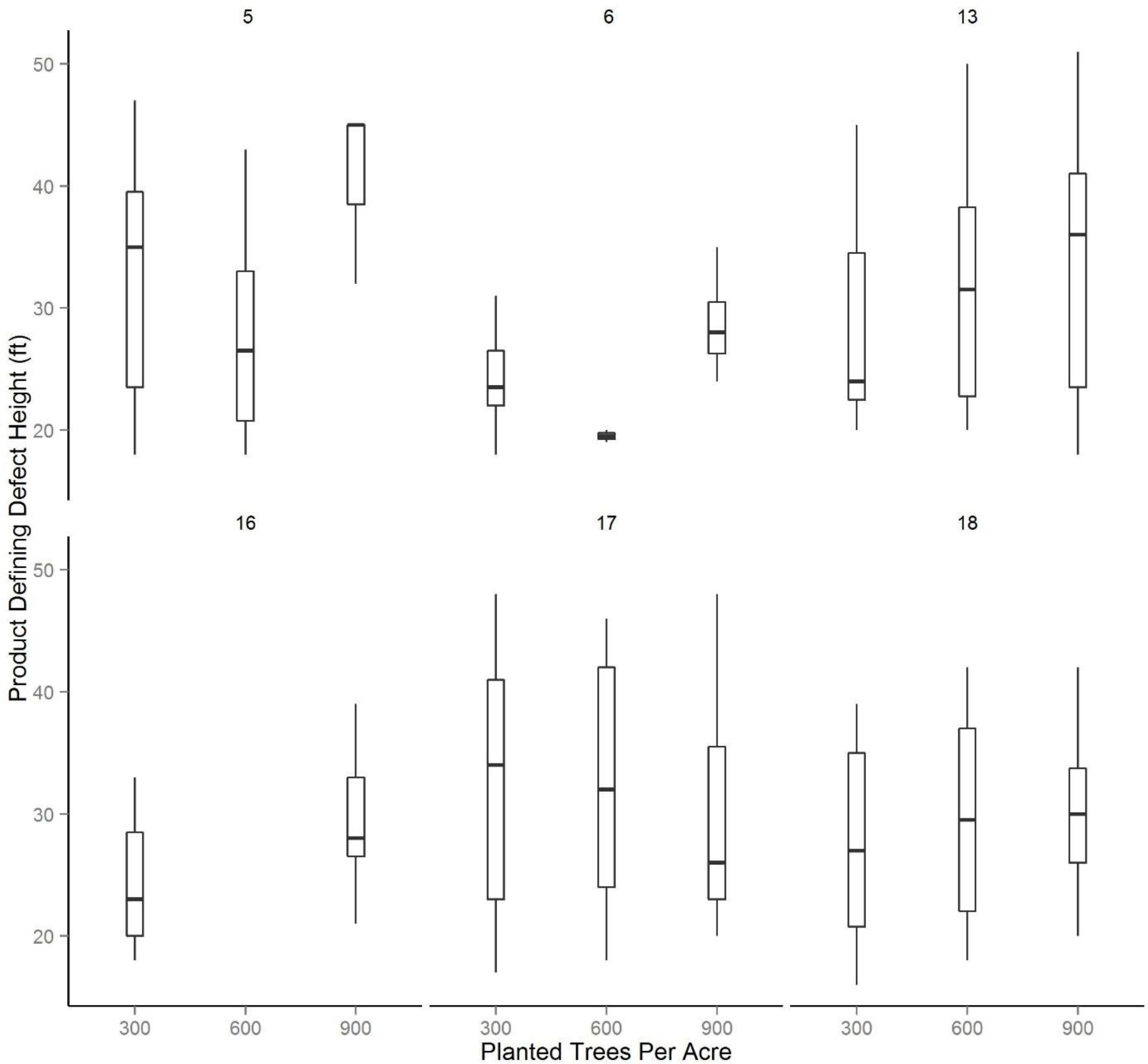

Figure 2.20: Product defining defect heights by planted trees per acre and installation (operational management only) for PMRC SAGS Culture x Density non-thinned sites.

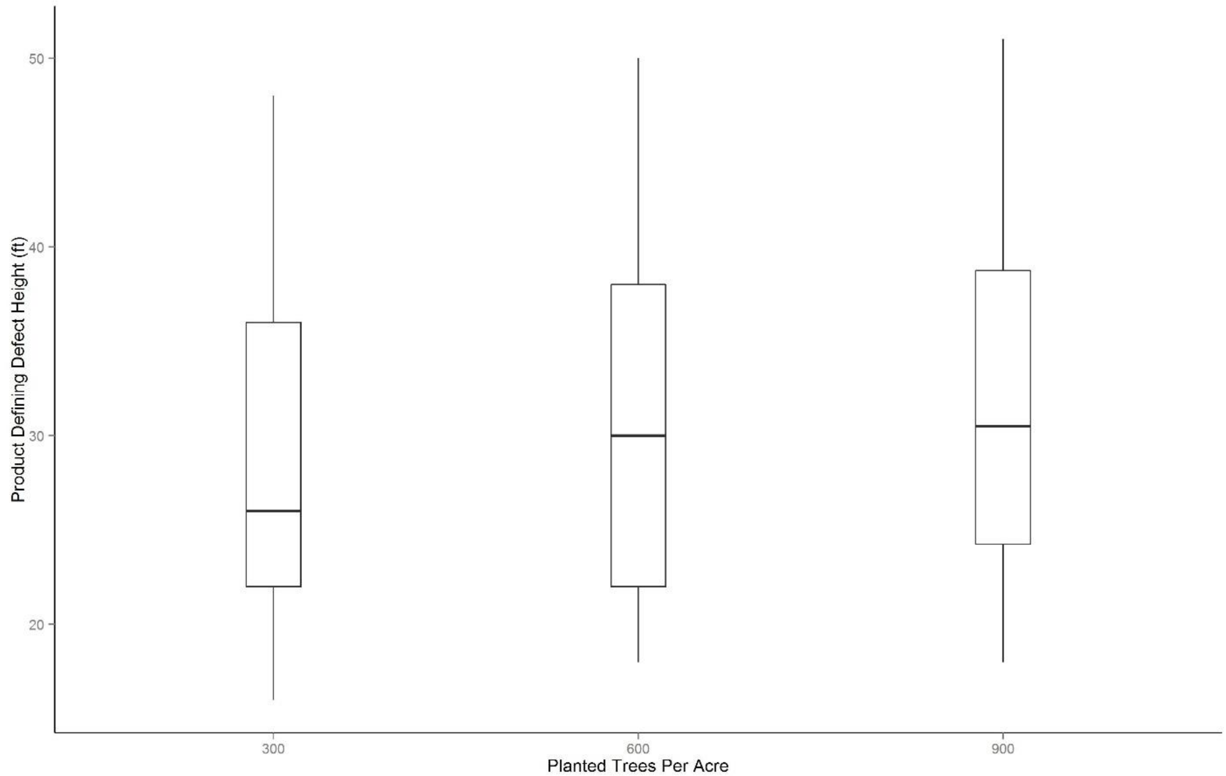

Figure 2.21: Product defining defect height by planted trees per acre for operational management only across all installations for PMRC SAGS Culture x Density non-thinned sites.

CHAPTER 3[2]

CULTURE INTENSITY AND STAND DENSITY EFFECTS ON TREE QUALITY IN MIDROTATION THINNED LOBLOLLY PINE PLANTATIONS IN THE SOUTHEAST

[2] Green, P. C., Kane, M. Bullock, B. Daniels, R., Lazar, N. To be submitted to Forest Science.

Abstract

Four thinned loblolly pine (*Pinus taeda*) culture x density studies in the Piedmont and Upper Coastal Plain of the Southeast, the Plantation Management Research Cooperative (PMRC) South Atlantic Gulf Slope (SAGS) studies, were used to examine the effects of two cultural intensities, four planting densities, and their interactions on solid wood potential as well as the proportion and position of product defining defects. Product defining defects are defined as stem defects that limit any solid wood products past the defection. Forking, crooks, and broken tops are examples. A tree quality index (TQI), was used to grade standing timber for solid wood potential. All product defining defects were measured to the nearest foot. Results show that operational management intensity produced a higher proportion of trees with solid wood product potential than did the intensive management. Operational management exhibited fewer product defining defects. Further, the average product defining defect position was higher on the stem in operational management. Densities that received thinning exhibited greater proportions of stems with solid wood product potential than did the non-thinned 300 tree per acre counterpart. These results suggest that management intensity is a major driver of tree quality and that thinning improves overall tree quality in a stand.

Introduction

Of all the southern pines, loblolly pine has the largest native range and is the most commonly planted species in the South (Martin and Shiver 2002). Demands are expected to increase globally for southern wood products, therefore, there will be an increased importance on effectively managing loblolly pine in the future (Fox 2000).

Of all the management decisions made for a pine plantations, the choice of planting density is one of the most important decisions made by a forester (Amateis and Burkhart 2012). It is well known that planting density affects many stand attributes. Higher density stands exhibit smaller average breast height diameter, higher standing volume, and higher partitioning to stems and branches (Zhao et al. 2012). Studies that have examined the effects of planting density on average dominant height have shown varied results. Slash pine grown at a variety of densities in South Africa resulted in no significant differences in dominant height (Pienaar and Shiver 1984) while planted loblolly in southeastern Oklahoma showed deceasing height with increasing density (Hennessey et al. 2004). In a rotation length loblolly pine spacing trail in the Virgina and North Carolina Piedmont and Coastal Plain, it was concluded that there is no one planting density that is optimal for every management objective (Amateis and Burkhart 2012).

Thinning is one of the most common silviculture treatments used by forest managers to influence stand conditions. Thinning reduces stand density and concentrates growth on the residual stand. There are several methods of thinning commonly used by foresters. Thinning from below, or low thinning, removes trees in lower crown positions. This allows trees that have already expressed dominance to more freely use the available site resources. Thinning from above, or high thinning, removes some of the dominant trees to favor the highest quality trees. This allows growth to be focused more on quality, not strictly quantity. Selection thinning removes dominant trees to favor smaller individuals that have high form quality. Mechanical thinning, or geometric thinning removes trees in a fixed pattern. In the loblolly pine plantation system, this involves removing every n^{th} row. Free thinning is a method that releases selected crop trees in the stand. This method combines thinning criteria to release only selected trees. In southern pine systems, a hybrid method of row thinning and free thinning is typically used for first thinning (Nyland 2002). Second thinning is usually a free thinning of some type. All of these methods can be used with varying levels of intensity to help realize different management goals. Often this goal is to grow higher proportions of high value solid wood products. A region-wide loblolly thinning study found that thinning significantly impacted the product distribution in the higher diameter classes (Amateis and Burkhart 2005). Previous work conducted on the same study found that thinning increased both height and diameter on individual trees. Higher thinning intensity increased individual loblolly pine growth more than lighter thinning (Zhang et al. 1997). A shortleaf pine thinning study in Mississippi found that regardless of the seven thinning methods chosen, by age 48, all thinning methods increased the total stand yield of sawtimber as compared with a non-thinned control plot (Williston, 1983). Thinning significantly helps control natural mortality that occurs in non-thinned conditions. In southeastern Oklahoma, non-thinned plots averaged 90 trees per hectare of mortality from age 10 to 24. Mortality losses in two thinning regimes were only 3.2 to 7.7 trees per hectare (Hennessey et al. 2004). A goal of many thinning operations is to concentrate growth onto larger, better formed trees to influence the end product proportions. Peelers, sawtimber, and other solid wood products are typically much higher valued products than fiber products. This leads many managers to use thinning as a tool to increase the yields of these higher valued commodities.

With the great advancements made in the growth of southern pine, especially loblolly pine, there has been limited research on how silviculture affects the stem quality trees. There have been assumptions made about the effects of silviculture, such as increased planting density results in higher stem quality, however quantifying how silviculture affects stem quality has proven challenging. Questions have arisen concerning how planting rectangularity effects tree quality. A spacing trial in Virginia and North Carolina showed that for spacing up to 1:3, there was no significant differences in stem quality (Amateis et al. 2004). A common silviculture assumption is that trees growing slower tend to exhibit better stem quality than trees that are going more rapidly. This assumption is supported by several studies. The quality of sawn Scots pine in Scandinavia was found to be inversely related to the radial growth of the main stem (Ikonen et al. 2009). In similar work in Sweden, it was shown that higher productivity soils were found to produce lower quality Scots pine than lower productivity soils (Teglemark 1999). In uneven-aged southern pine stands, low productivity sites tended to carry trees with higher stem quality than higher productivity sites (Prestemon and Buongiorno 2000). There is no known research on the effect of the combination of stand density and culture on stem quality for southern pine systems.

The South Atlantic Gulf Slope (SAGS) culture x density study was installed by the Plantation Management Research Cooperative (PMRC) in 1998 to study the combined effects on loblolly pine stand development with six levels of planting density and two levels of management intensity. The study was establish across a wide geographic range covering the Piedmont and Upper Coastal Plain of the southern United States. A number if these installations had a targeted thinning age of around 10 to 12 years old. This study has provided large amounts of valuable information regarding the development of loblolly pine stands. The influence that both management intensity and planting density have on stand development is pronounced (Wang et al. 2104). Lacking in reported results of this study are how the combined effects of planting density and culture intensity effect stem form and the presence and position of product defining defects. The present research examines culture and density impacts on stem quality on installations with thinning using a method to grade standing trees for their product potential. This system, known as the Tree Quality Index or TQI, is a simple, effective method used to operationally grade stems in many operational timber inventories. On any tree with a product defining defect such as a fork or broken tops, the height on the stem where the defected occurred was measured. This research helps to improve our understanding of how density and management affect tree quality. This research aids forestland managers in making more informed decisions when establishing loblolly pine plantations in the Southeast.

Hypothesis

1. More intensive management of loblolly pine will decrease overall tree quality in thinned stands.
2. Within operational planting densities, a higher planting density will result in improved stem quality in loblolly pine in thinned stands.
3. Management intensity and planting density will affect the average quantity and position of product defining defects in thinned stands.
4. There will be interaction of management intensity and planting density in loblolly pine plantations with better quality with the higher density and operational culture combination.
5. Thinning will increase the proportion of trees with solid wood potential in a stand.

6. Thinning will decrease the proportion of product defining defects as well as affect their average position in a stand.

Methods and Materials

Site Description

This research utilized four loblolly pine installations distributed across the Georgia Piedmont as well as the Alabama and Florida Upper Coastal Plain (Figure 3.1). These sites are part of the South Atlantic Gulf Slope (SAGS) Culture Density study and are all managed by the University of Georgia Plantation Management Research Cooperative (PMRC). PMRC tree measurements in this study were taken at 15 years old. The installations cover a range of geographic provinces and soil series (Table 3.1). All installations were on upland, well drained sites common to this region.

At each thinned installation, the following four planting densities were utilized for this study: 300, 600, 900, and 1200 planted trees per acre. At all installations, two management intensities were utilized. The operational treatment consisted of early competition control and several fertilization treatments. The intensive treatment consists of many fertilizations and complete competition control (Table 3.2). At each installation, a split-plot design was used. The main plots consisted of the two management intensities while the subplots consisted of six planting densities (the 1500 and 1800 tree per acre sub-plots were not utilized in this research). Planting on each site occurred in 1998, except for the Santa Rosa County site which was re-planted in 1999, and seedlings were sourced by the PMRC cooperator in charge of the given installation. At each planting location, seedlings were double planted and were reduced to one seedling after the first growing season. This ensured adequate survival on each plot. Plot size varied by planting density (Table 3.3), and each plot contains a measurement plot surrounded by a buffer approximately 26 feet wide to eliminate possible edge effects.

The 600, 900, and 1200 planting density plots received a mechanical thinning plus selection at age 10 on Installation7 and at age 12 on Installations 3, 11, and 12. Each plot was thinned to a target tree per acre to meet the current trees per acre of the 300 planted trees per acre plots at the corresponding installation and cultural treatment.

Measurements

Diameter at breast height (DBH) was measured on every tree in the measurement plot to the nearest 1/10th of an inch. Total height and height to live crown were measured on every other tree to the nearest foot. Those trees without measured heights were estimated using the following linear regression model: $\ln(H) = \beta_0 + \beta_1(D^{-1})$ with data collected from trees with measured heights. Age 15 stand parameters are displayed in Table 3.4.

During the age 15 growing season for the Florida site and the age 16 growing season for all other sites, additional 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 was measured with a laser hypsometer to the nearest foot. 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 (Table 3.5). A score of 1 indicates that the tree has solid wood product potential and is free of any moderate to major defects including disease, crook, sweep, large knots, forks, or broken tops below 48 feet. Trees with product defining defects or disease above 48 feet can be classified as a TQI 1. A tree assigned a TQI 2 has solid wood potential but has defects that will limit its merchantability. Moderate sweep, crook, disease, and knots are acceptable. Product defining defects are allowed above 16 feet. A tree assigned a TQI 3 has major defects that will eliminate any solid wood product potential. Once classified as a TQI 3, a given tree is assumed to be pulpwood forever. A tree assigned a TQI 4 has major defects such as serious disease, very poor form, or extremely stunted growth, that will preclude any merchantability. This tree is classified as cull. It is important to note that the TQI system scores tree product potential, not necessarily current product. If a defect was present in the lower 10 feet of the tree that did not seriously affect the product potential of the stem, the height of this defect, also known as a jump butt, was measured and recorded. An example of such defect would be a rust gall in the first 2 feet of the stem. Such a defect would commonly be removed in a harvest and the rest of the stem would be merchandized accordingly.

Analysis

All analysis conducted for this research was conducted using the R statistical package (R Core Team 2014). All graphics were developed using the packages ggplot2 (Wickham 2009) and vcd (Meyer et al. 2014).

Analysis of Tree Quality Index Data

With the tree quality index being an ordered categorical response, traditional ANOVA methods are not typically considered appropriate for working with this type of data analysis. Chi-squared type analysis was used for analyzing this type of categorical data. Mosaic plots were used to graphically represent the deviation of independence when analyzing both planting density and management intensity's effects together on tree quality per Simonoff (2003).

The structure of the TQI method lends itself well to a transformation to a binary response. TQI 1 and TQI 2 can be combined to a 1, which is yes the tree has solid wood product potential. TQI 3 and TQI 4 can be combined to a 0, which is the tree does not have solid wood product potential. While this does dilute the data, transforming to a binary format allows for expanded analysis methods. When transformed into the binary format, proportion comparison tests are an appropriate analysis method.

Using ANOVA to analyze categorical data is not usually recommended. While the TQI scores are numeric, they are actually ordinal categorical measurements. With this said, the use of an ANOVA to analyze this type of information may be informative. While this should not be seen as formal analysis, it can be used to reinforce other results. A two-way ANOVA was used to compare “average” TQI scores across management intensity and stand density. The interactions between installation, management, and density were also examined.

Analysis of Product Defining Defects Data

Analysis of product defining defects is considered for both the proportion of stems with these defects as well as the average height at which the defects occur. Being a binary response, the analysis of proportions of stems with product defining defects can be approached through both proportion tests and chi-squared goodness of fit tests. Being a numerical response, the heights of the defects were analyzed through a two-way ANOVA design. In the two-way ANOVA, installation, management intensity, planting density, and their interactions were analyzed. The two-way ANOVA will be an unbalanced design due to missing defect height observations in the data. If an individual tree does not have a defect, a value cannot be recorded. Any value entered that is not a defect will incorrectly factor into the average defect height. Because of this limitation, an unbalanced design was employed.

Results

Tree Quality

Management intensity significantly affected the distribution of TQI scores. Intensive management reduced the number of stems that scored in the higher quality classes compared with the operational management across all installations (Figure 3.2). When viewed as a binary yes or no for solid wood product potential, the same result was found (Figure 3.3). In the thinned stands, there were noticeable differences in the distribution of TQI scores across densities (Figure 3.4). The same results were seen when viewed in the binary solid wood potential format (Figure 3.5). It was expected that the 300 tree per acre planting density would be significantly different from the other densities and the results of this study support this expectation. The 300 tree per acre density exhibits the lowest proportion of stems in the TQI 1 and 2 categories and the lowest proportion of stems that exhibit solid wood product potential. When the effects of management intensity were averaged across installations, the intensive management reduced the proportions of stems that were graded in the highest two TQI classes (Figure 3.6). The proportion of stems that exhibited solid wood product potential in intensively managed plots was statistically different than on operational plots at α=0.05 level (Table 3.6). When the effects of planting density were averaged across all installations, the 300 tree per acre planting density exhibited the smallest proportion of stems that were graded in the highest two product classes (Figure 3.7). The proportion of stems that stems that exhibited solid wood product potential was significantly different among the planting densities at α=0.05 level (Table 3.7). The mosaic plot effectively shows the influence of planting density and management intensity on the distribution of TQI scores (Figure 3.8) and the proportions of trees with solid wood potential (Figure 3.9).

The results of the two-way ANOVA confirmed that there were significant differences among installation, management intensity, planting density, and the interaction between management and density at α=0.05 level (Table 3.8).

Product Defining Defects

The heights of product defining defects varied by management intensity by installation (Figure 3.10). There were not clear patterns observed across installations for defect height. When viewed across installations, intensive management resulted in lower product defining defect heights (Figure 3.11). Management intensity does appear to influence the proportion of the defects. Intensive management exhibits more defects than operational management when viewed by installation (Figure 3.12). The heights of product defining defects follows no clear pattern by planting density for the thinned installations (Figure 3.13). When viewed averaged across installations, height of the defects increased as planting density increased up to the 900 tree per acre density (Figure 3.14). The proportion of product defining defects did not appear to be influenced by planting density in thinned installations (Figure 3.15). When averaged across installations, intensive management exhibited more stems with product defining defects (Figure 3.16), and the 300 tree per acre density exhibited the most stems with defects (Figure 3.17).

The proportion of stems that exhibit product defining defects is significantly higher in intensive management when analyzed across all installations. This result is significant at α=0.05 (Table 3.9). The proportion of stems that exhibit product defining defects is not statistically significant at α=0.05 across the four planting densities (Table 3.10). A two-way ANOVA was utilized to test for significant differences in product defining defect heights for installation, planted trees per acre, management intensity, and interaction between management and density. Significant differences were found among installations and planted trees per acre for product defining defect height at α=0.05. Differences in management intensity were slightly not significant with a P-value = 0.06 at α=0.05. No significant interactions between density and management were found at α=0.05 (Table 3.11).

Discussion

Tree Quality

The effects of management intensity on tree quality parallel those found in the non-thinned installations. Plots that received intensive management exhibited lower overall tree quality than did the operational management plots. This result is not surprising as several published studies have shown that slower growing trees produce higher quality saw logs (Ikonen et al. 2009). It was expected that the 300 tree per acre density would be significantly different in terms of proportions of solid wood product potential stems. Because this density did not receive thinning, a higher proportion of lower quality stems are left that would be removed during thinning. Thinning artificially removes trees from a stand and ideally, these should be stems that exhibit little to no potential for higher valued solid wood products. In the higher density plots, thinning removed lower quality stems in favor of higher quality stems. The slight decrease in proportions of stems with solid wood product potential at the 1200 tree per acre planting density compared with the 900 tree per acre planting density was surprising. It is possible that stems planted at this high density aggressively compete for light thus negatively affecting their form compared with slightly lower densities. The hypothesis that higher planting density results in better tree quality can be cautiously supported. Planting density was found to have little influence on tree quality in the non-thinned installations and with the thinned installations, the selection component of the thinning operation could dilute any effect that density may have had on tree quality. It is important to note that this is a point in time measurement. If observations were made over time, it is very possible that significant changes in tree quality would occur as the studies mature.

While assessing differences in tree quality among a variety of site productivity levels was not an objective of this study, it has been noted that lower productivity sites exhibit higher quality saw logs compared to sites exhibiting more rapid growth (Stahl et al. 1990). Differences in tree quality due to differing growth rates over a range of geographic locations can be related to various levels of management intensity in similar base growing conditions and regions. Higher management intensity increases tree growth rates as does improving growing conditions due to better sites. With the results of the current study on how more rapid growth rates affect stem quality due to either management or geographic region, more informed management decisions can be made when managing for higher valued solid wood products. If intensive management results in significant growth increases at a large expense of overall tree quality, the additional investment for the increased growth may result in a lower net present value for the rotation due to a reduction of stem quality.

Product Defining Defects

As with tree quality, plots that received intensive management resulted in an increase of the proportion of stems with product defining defects and a lower average defect height even though this result was slightly not significant at $\alpha=0.05$ with a P-value of 0.06. While this result is not surprising because the thinned installations received the same intensive management that the non-thinned installations received, there is no known published research to help explain the reason for these differences. It is possible that intensive management provides the necessary resources to encourage multiple dominant leaders that lead to forking. Further, it is possible that rapid growth encourages crooks, and weakened wood that breaks easily leading to broken tops. Product defining defects are a significant driver for overall tree quality and the presence of a defect should be taken into consideration when planning to harvest a tree. Some defects reduce the economic value of a tree very little. A broken top at the top of a mature tree is insignificant compared with multiple dominant leaders that begin low on a stem. While both are product defining defects, the severity of the defect should always be considered.

Across planting densities, product defining defect heights appear to increase as density increases. The average height of the defects was statistically different among densities however this is not a strong trend. There was no observable trend in proportion of stems with product defining defects across densities. This was a surprising result as it was expected that the thinned and non-thinned densities would show clear differences in proportions of product defining defects.

The TQI assessment method chosen to evaluate tree quality was selected because it is a common method to grade standing trees in operational timber inventories. While the hypothesis that the TQI method is a strong method for grading standing trees is supported, it is of the opinion of the author that more information should have been collected to supplement the TQI quality assessments. A reason for each assessment would have provided valuable information at the expense of time. An example would be a tree downgraded from a TQI 1 to 2 because of branching. Further, if quality assessments could be independently audited, a level of rigor could be added to the results presented. The PMRC SAGS study was selected because of its large geographic range, the experimental design, and the amount of legacy data available. Similar studies exist in the Lower Coastal Plain and Western Gulf regions of the southern United States that could be used for expanding this research. Larger numbers of installations would have perhaps provided the ability to develop stand level predictive models to help describe tree quality with stand level parameters, management intensity, and planting density as inputs. The largest limitation with this study is the lack of more thinned installations to sample. Only having four installations available limits the ability to analyze more subtle trends that may only become apparent with a larger sample size.

Conclusions

The influence of management intensity on tree quality and product defining defects was consistent in the thinned installations as in the non-thinned installations. The hypothesis that intensive management reduces tree quality was supported. Tree quality was reduced under intensive management and it appeared that the frequency and position of product defining defects was significantly influenced. These results support the hypothesis that intensive management increases the proportion and lowers the average height of product defining defects. The reduced numbers of product defining defects in thinned stands was expected. Stems with product defining defects are often chosen for removal in the selection portion of a thinning regardless of the position on the stem. Often, lower quality stems without product defining defects are retained in the stand compared to stems with a product defining defect present high on a stem.

The significant differences in TQI percentages across planting densities confirmed the relationship hypothesized. Due to the 300 tree per acre planting density plots not being thinned, they exhibit more trees of lower quality. The hypothesis that management and density interact was supported for the TQI analysis and not supported for the product defining defect analysis. The results of this study show interaction between management and culture on TQI scores, however, there was no interaction for product defining defect height.

In conclusion, the results of this study show that management intensity, and planting density both influence tree quality in thinned installations compared with non-thinned counterparts. Using this information, along with known stand effects of management and density affects, should provide managers with the ability to maximize value in managed loblolly pine in the Southeast.

Literature Cited

Amateis, R. L., and Burkhart, H. E. 2012. Rotation-age results from a loblolly pine spacing trial. Southern Journal of Applied Forestry 36(1): 11-18.

Amateis, R. L., and Burkhart, H. E. 2005. The influence of thinning on the proportion of peeler, sawtimber, and pulpwood trees in loblolly pine plantations. Southern Journal of Applied Forestry 29(3): 158-162.

Amateis, R. L., Radtke, P. J., and Hansen, G. D. 2004. The effect of spacing rectangularity on stem quality in loblolly pine plantations. Canadian Journal of Forest Research 34: 498-501.

Fox, T. R. 2000. Sustained productivity in intensively managed forest plantations. Forest Ecology and Management 138: 187-202.

Hennessey, T. C., Dougherty, P. M., Lynch, T. B., Wittwer, R. F., and Lorenzi, E. M. 2004. Long-term growth and ecophysical responses of a southeastern Oklahoma loblolly pine plantation to early rotation thinning. Forest Ecology and Management 192: 97-116.

Ikonen, V. P., Kellomaki, S., and Peltola, H. 2009. Sawn timber properties of Scots pine as affected by initial stand density, thinning and pruning: A simulation based approach. Silva Fennica 43(3): 411-431.

Martin, S. W., and Shiver, B. D. 2002. Impacts of vegetation control, genetic improvement and their interaction on loblolly pine growth in the southern United States – age 12 results. Southern Journal of Applied Forestry 26(1): 37-42.

Meyer, D., Zeileis, A., Hornik, K. 2014. vcd: Visualizing Categorical Data. R package version 1.3-2.

Nyland, R. D. 2002. Silviculture: Concepts and Applications. McGraw-Hill Co., New York. 2ed. 407-428. 682 pp.

Pienaar, L. V., and Shiver, B. D. 1984. The effect of planting density on dominant height in unthinned slash pine plantations. Forest Science 30(4): 1059-1066.

Prestemon, J. P., and Buongiorno, J. 2000. Determinants of tree quality and lumber value in natural uneven-aged southern pine stands. Canadian Journal of Forest Research 30: 211-219.

R Core Team (2014). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Simonoff, J.S. 2003. Analyzing Categorical Data. Springer, New York. 213p.

Stahl, E.G., Persson, B., and Prescher, F. 1990. Effect of provenance and spacing on stem straightness and number of stems with spike knots in *Pinus sylvestris* L. – Northern Sweden and countrywide models Sudia Forestalia Suecica 184: 1-16.

Teglemark, D. O. 1999. Prediction of stem properties based on climate and soil factors in naturally regenerated *Pinus sylvestris* stands. Scandinavian Journal of Forest Research 14: 131-142.

Wang, M., Kane, M., and Zhao, D. 2014. SAGS Culture/Density Study: Age 15 Results. PMRC Technical Report 2014-2. Plantation Management Research Cooperative, Warnell School of Forestry and Natural Resources, University of Georgia. Athens, GA. 82pp.

Wickham, H. 2009. ggplot2: Elegant graphics for data analysis. Springer, New York.

Williston, H.L. 1983. Management of shortleaf pine plantations in North Mississippi. Southern Journal of Applied Forestry 7(4): 194-197.

Zhang, S., Burkhart, H. E., Amateis, R. L. 1997. The influence of thinning on tree height and diameter relationships in loblolly pine plantations. Southern Journal of Applied Forestry 21(4): 199-205.

Zhao, D., Kane, M., Borders, B. E., Subedi, S., and Akers, M. 2012. Effects of cultural intensity and planting density on stand-level aboveground biomass production and allocation for 12-year-old loblolly pine plantations in the Upper Coastal Plain and Piedmont of the southeastern United States. Canadian Journal of Forest Research 42: 111-122.

Tables and Figures

Table 3.1: Geographic details, soil details, and site quality for PMRC SAGS Culture x Density thinned installation utilized SAGS thinned installations site details.

Installation	County	State	Physiographic Province	NRCS Soil Series	Soil Taxonomy	Site Index*
3	Escambia	AL	Upper Coastal Plain	Freemanville	Fine, kaolinitic, thermic Plinthic Kandiudults	79
7	Santa Rosa	FL	Upper Coastal Plain	Troup	Loamy, kaolinitic, thermic Grossarenic Kandiudult	79
11	Greene	GA	Piedmont	Cecil	Fine, kaolinitic, thermic Typic Kanhapludults	82
12	Barbour	AL	Upper Coastal Plain	Orangeburg - Springhill	Fine-loamy, kaolinitic, thermic Typic Kandiudults	86

*Site index is shown for operational culture planted at 600 trees per acre with a base age of 25

Table 3.2: Detail of cultural regimes utilized in PMRC SAGS Culture x 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: 500 lbs/ac 10-10-10 Before year 8: 200 lbs/ac N + 25 lbs/ac P Before year 12: 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 Before year 10: 200 lbs/ac N + 25 lbs/ac P Before year 12: 200 lbs/ac N + 25 lbs/ac P Before year 14: 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

Table 3.3: Planting density plot sizes for PMRC SAGS Culture x Density study.

Planting Density (TPA)	Spacing (ft. x ft.)	Trees per measure plot	Measure plot size (ac)	Gross plot size (ac)
1800	6 x 4	184	0.1	0.31
1500	6 x 4.8	160	0.11	0.32
1200	6 x 6	120	0.1	0.3
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

Table 3.4: Stand attributes of thinned PMRC SAGS Culture x Density stands at age 15 by management intensity and initial planting density.

INST	MAN	PTPA	TPA	MDBH	MHT	MCRNRAT	HD	TVOB	GWOB	BA	SDI
3	Intensive	300	219	10.8	62	0.50	62	4033	109	141	250
3	Intensive	600	234	9.4	63	0.41	63	3332	90	114	214
3	Intensive	900	265	8.7	62	0.41	63	3141	85	110	212
3	Intensive	1200	262	7.9	59	0.40	61	2507	68	90	181
3	Operational	300	231	9.1	57	0.45	60	2901	78	105	200
3	Operational	600	189	8.2	54	0.52	56	1830	49	71	141
3	Operational	900	208	8.1	52	0.45	56	1937	52	76	151
3	Operational	1200	232	7.1	53	0.47	54	1619	43	65	137
7	Intensive	300	284	9.4	57	0.49	57	3710	99	140	262
7	Intensive	600	272	8.7	56	0.49	57	3041	82	114	220
7	Intensive	900	293	8.0	55	0.47	57	2660	71	102	204
7	Intensive	1200	282	8.0	55	0.48	55	2612	70	100	200
7	Operational	300	287	9.5	58	0.42	57	3859	104	142	266
7	Operational	600	280	8.2	55	0.41	55	2743	74	105	206
7	Operational	900	284	7.9	56	0.39	57	2561	69	96	194
7	Operational	1200	292	7.6	55	0.45	58	2435	66	92	188
11	Intensive	300	295	9.5	53	0.46	54	3437	94	147	275
11	Intensive	600	272	8.8	51	0.47	53	2670	72	116	223
11	Intensive	900	312	7.7	59	0.43	59	2787	75	103	209
11	Intensive	1200	302	7.8	53	0.43	54	2429	65	100	203
11	Operational	300	284	9.5	56	0.45	57	3491	96	141	263
11	Operational	600	287	8.4	57	0.43	59	2886	78	112	219
11	Operational	900	303	7.4	51	0.43	54	2162	57	90	187
11	Operational	1200	282	7.3	54	0.39	54	2074	55	83	172
12	Intensive	300	295	10.7	65	0.45	65	5501	149	185	330
12	Intensive	600	280	9.0	64	0.35	66	3733	102	124	238
12	Intensive	900	303	8.2	63	0.36	62	3268	89	111	221
12	Intensive	1200	302	8.0	63	0.38	63	3112	85	106	212
12	Operational	300	280	9.8	63	0.37	64	4333	118	148	273
12	Operational	600	287	8.5	61	0.33	62	3366	92	116	225
12	Operational	900	303	7.8	62	0.37	63	2952	81	102	205
12	Operational	1200	313	7.9	61	0.38	64	3170	86	109	218

INST = Installation. **MAN** = Management intensity. **PLTPA** = Planted trees per acre. **TPA** = Current trees per acre. **MDBH** = Average Diameter at Breast Height (inches). **MHT** = Average height (feet). **MCRWNRAT** = Average crown ratio. **HD** = Average dominant height (feet).**TVOB** = Volume outside bark (ft^3). **GWOB** = Green weight outside bark (tons). **BA** = Basal area per acre (ft^2). **SDI** = Stand density index

Table 3.5: Tree Quality Index (TQI), specifications utilized for grading standing trees in the PMRC SAGS Culture x Density study.

TQI Class	Specifications
1	No defects that would limit any solid wood potential. No product defining defects below 48 feet.
2	Moderate defects that will limit solid wood potential. No product defining defects below 16 feet.
3	Major defects that eliminate solid wood potential. Pulpwood forever.
4	Serious defects that eliminate all merchantability. Cull.

Table 3.6: Two-sample test for equality of proportion of stems without solid wood product potential for two levels of management across all installations in PMRC SAGS Culture x Density study thinned installations evaluated.

2-sample test for equality of proportions	
Chi-squared = 26.12, df = 1, p-value < 0.0001	
prop 1 (Int. Man)	prop 2 (Op. Man)
0.177	0.079

Table 3.7: Four-sample test for equality of proportions of stems without solid wood product potential for four levels of planting density across all installations in PMRC SAGS Culture x Density study thinned installations evaluated. The 600, 900, and 1200 tree per acre plots were thinned to the 300 TPA density at age 12 on Installations 3, 11, and 12 and age 10 at Installation 7.

4-sample test for equality of proportions			
Chi-squared = 43.88, df = 3, p-value < 0.0001			
prop 1 (300 ptpa)	prop 2 (600 ptpa)	prop 3 (900 ptpa)	prop 4 (1200 ptpa)
0.196	0.108	0.043	0.077

Table 3.8: Two-way ANOVA for TQI values with test for interaction between PTPA and management for PMRC SAGS Culture x Density study thinned installations evaluated.

	Df	Sum Sq	Mean Sq	F Value	P Value
Installation	3	19.4	6.46	15.58	< 0.0001
PTPA	3	21.9	7.25	17.49	< 0.0001
Man	1	32.3	32.34	77.99	< 0.0001
PTPA:Man	3	4.5	1.51	3.63	0.013
Residuals	1279	540.3	0.42		

PTPA = Planted Trees per Acre
Man = Management Intensity

Table 3.9: Two-sample test for equality of proportions of stems without product defining defects by management intensity across all installations for PMRC SAGS Culture x Density study thinned installations evaluated.

2-sample test for equality of proportions	
Chi-squared = 8.466, df = 1, p-value = 0.0036	
Prop 1 (Int. Man.)	Prop 2 (Op. Man.)
0.74	0.81

Table 3.10: Four-sample test for equality of proportions of stems without product defining defects by planting density across all installations for PMRC SAGS Culture x Density study thinned installations evaluated. The 600, 900, and 1200 tree per acre plots were thinned to the 300 TPA density at age 12 on Installations 3, 11, and 12 and age 10 at Installation 7.

4-sample test for equality of proportions			
Chi-squared = 6.602, df = 3, p-value = 0.086			
prop 1 (300 ptpa)	prop 2 (600 ptpa)	prop 3 (900 ptpa)	prop 4 (1200 ptpa)
0.745	0.798	0.812	0.805

Table 3.11: Two-way ANOVA for product defining defect heights with interaction between PTPA and management intensity for PMRC SAGS Culture x Density study thinned installations evaluated.

	Df	Sum Sq	Mean Sq	F Value	P Value
Installation	3	2889	962.9	14.99	<.0001
PTPA	3	825	275.1	4.29	0.005
Man	1	221	3.442	4.00	0.064
PTPA:Man	3	100	33.3	0.52	0.67
Residuals	276	20016	72.5		

PTPA = Planted Trees per Acre

Man = Management Intensity

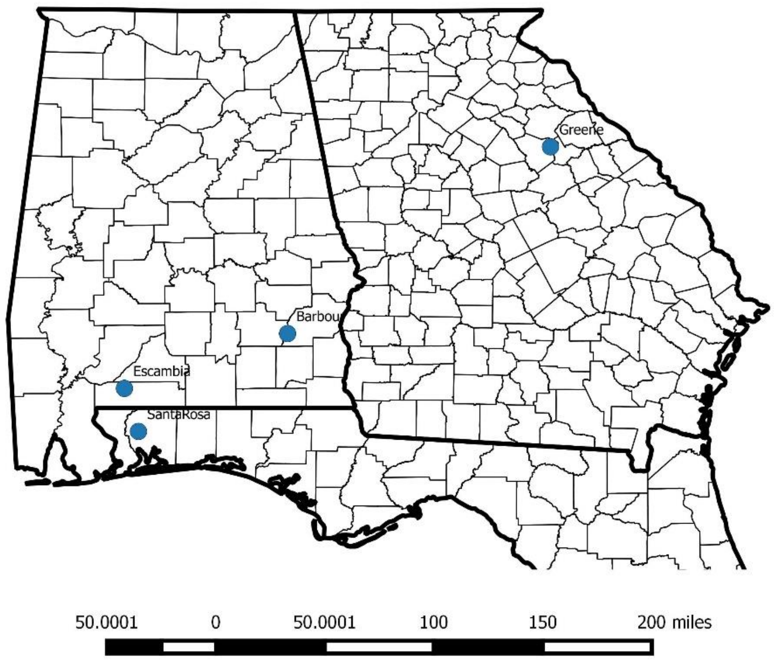

Figure 3.1: Location of PMRC SAGS Culture x Density thinned installations evaluated.

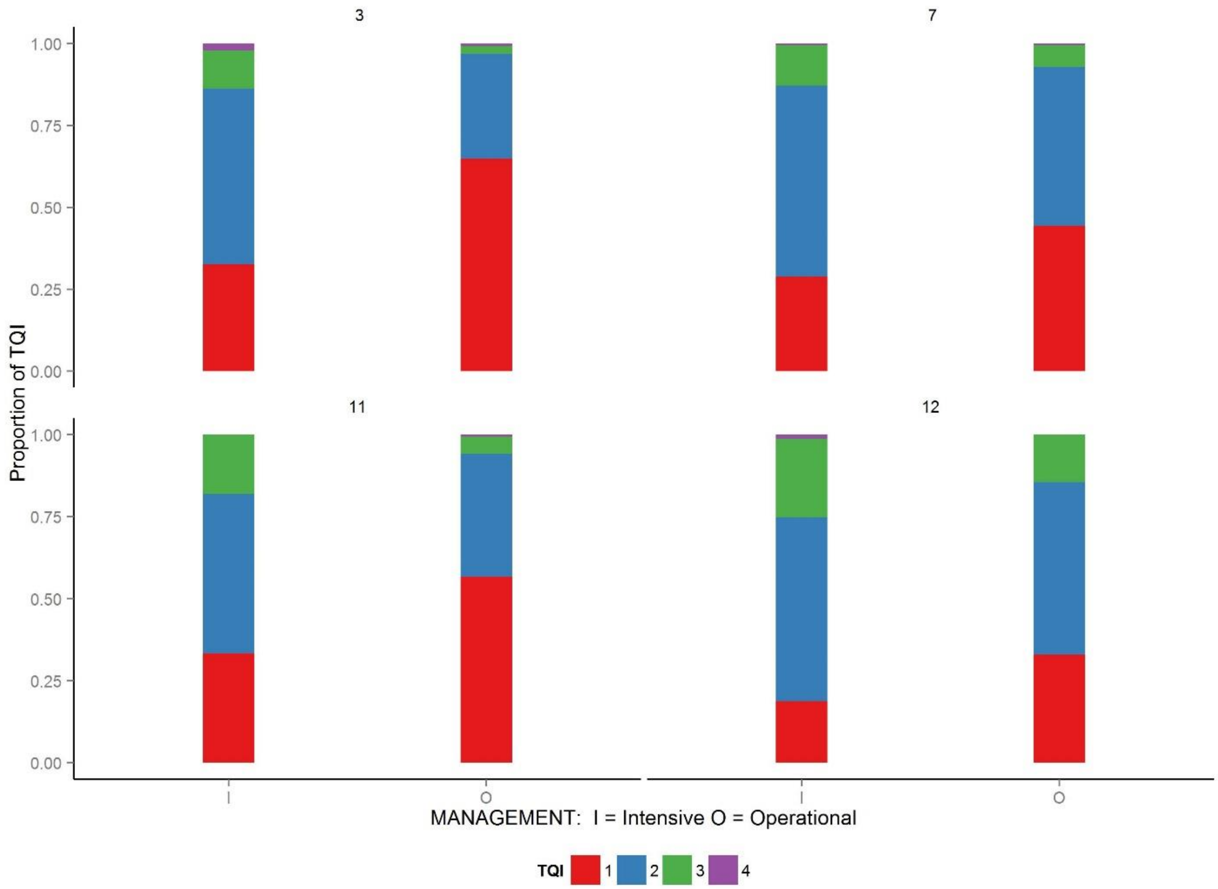

Figure 3.2: Proportion of stems in TQI classes by management intensity and installation for PMRC SAGS Culture x Density thinned sites.

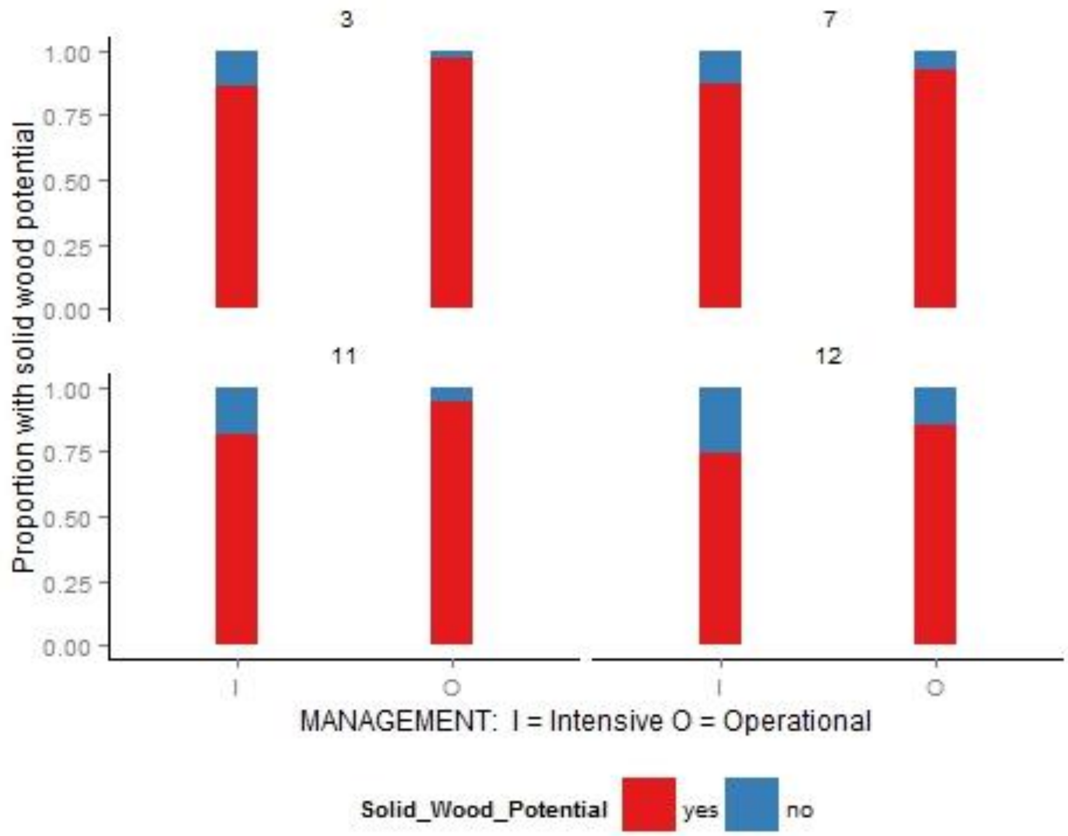

Figure 3.3: Solid wood product potential by management intensity and installation for PMRC SAGS Culture x Density thinned sites.

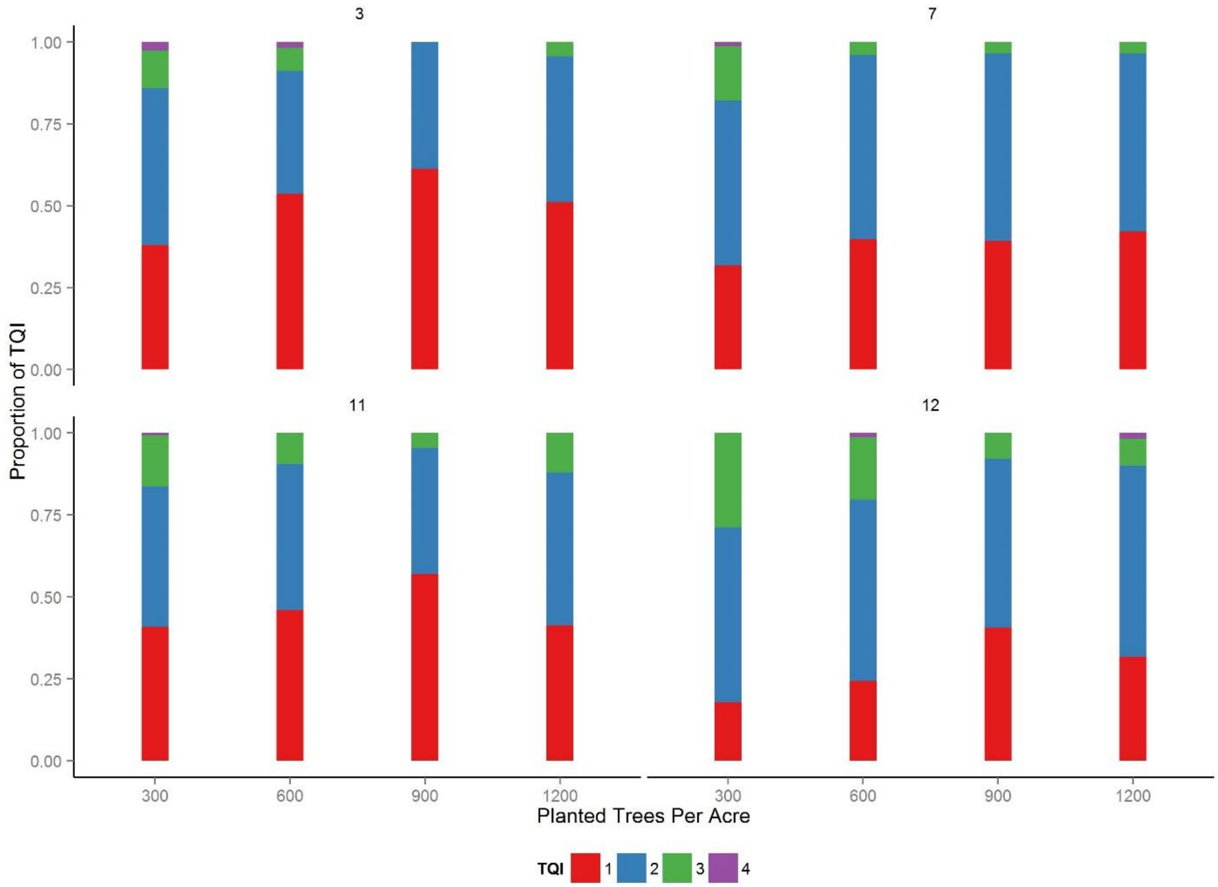

Figure 3.4: Proportions of stems in TQI classes by planting density and installation for PMRC SAGS Culture x Density thinned sites. The 600, 900, and 1200 tree per acre plots were thinned to the 300 TPA density at age 12 on Installations 3, 11, and 12 and age 10 at Installation 7.

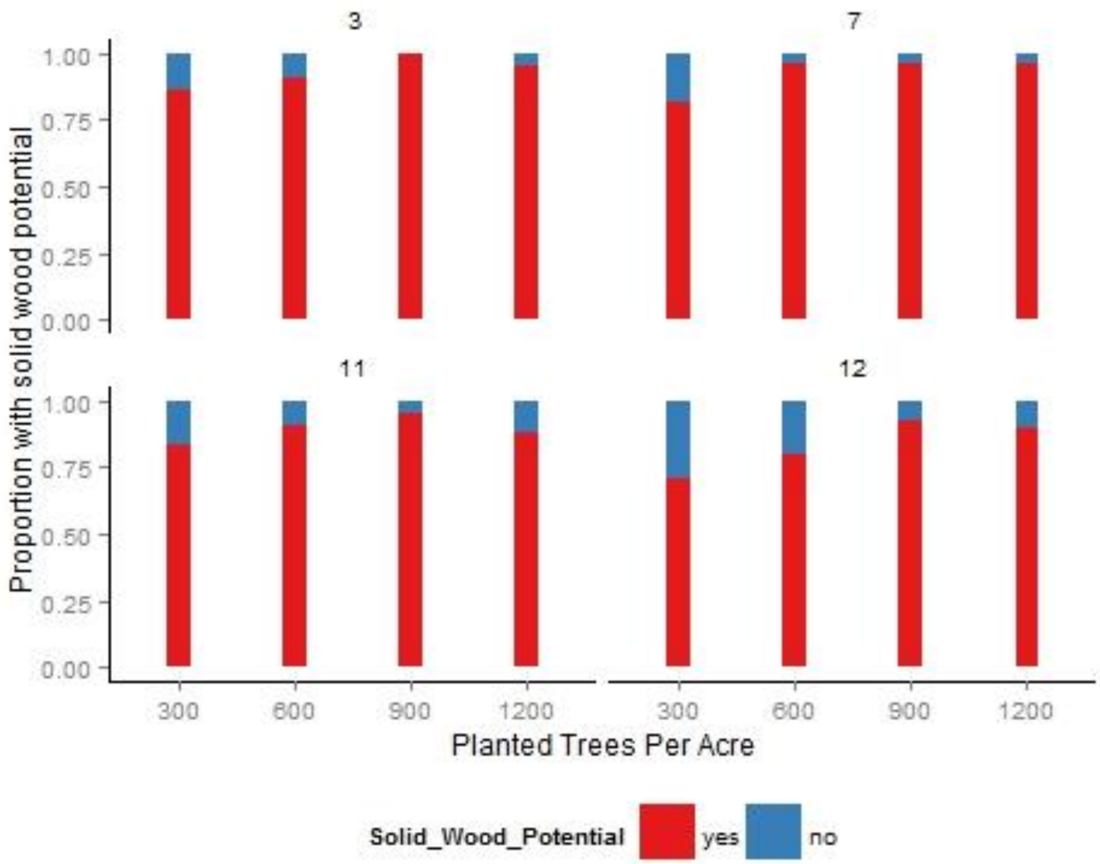

Figure 3.5: Solid wood product potential proportions across planting density and installation for PMRC SAGS Culture x Density thinned sites. The 600, 900, and 1200 tree per acre plots were thinned to the 300 TPA density at age 12 on Installations 3, 11, and 12 and age 10 at Installation 7.

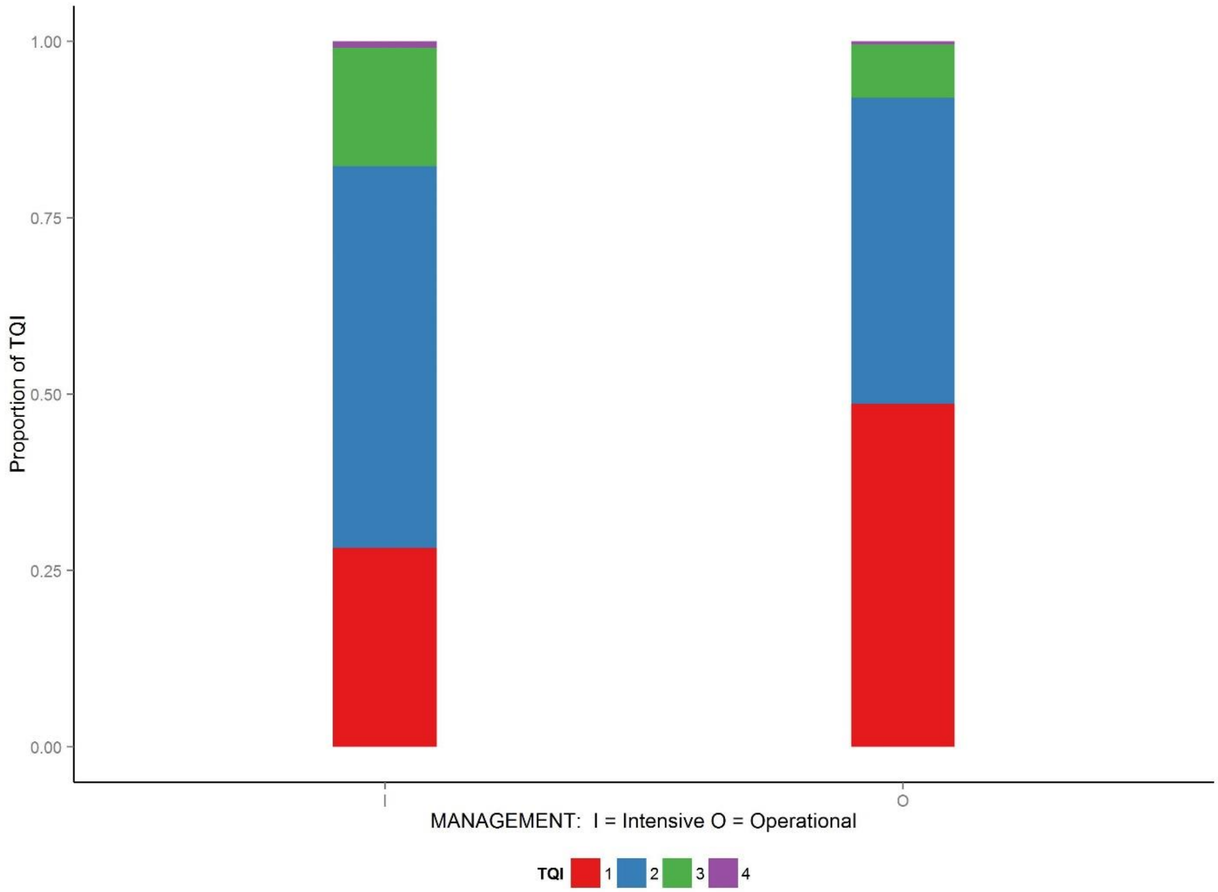

Figure 3.6: Proportion of TQI by management intensity across all installations for PMRC SAGS Culture x Density thinned sites.

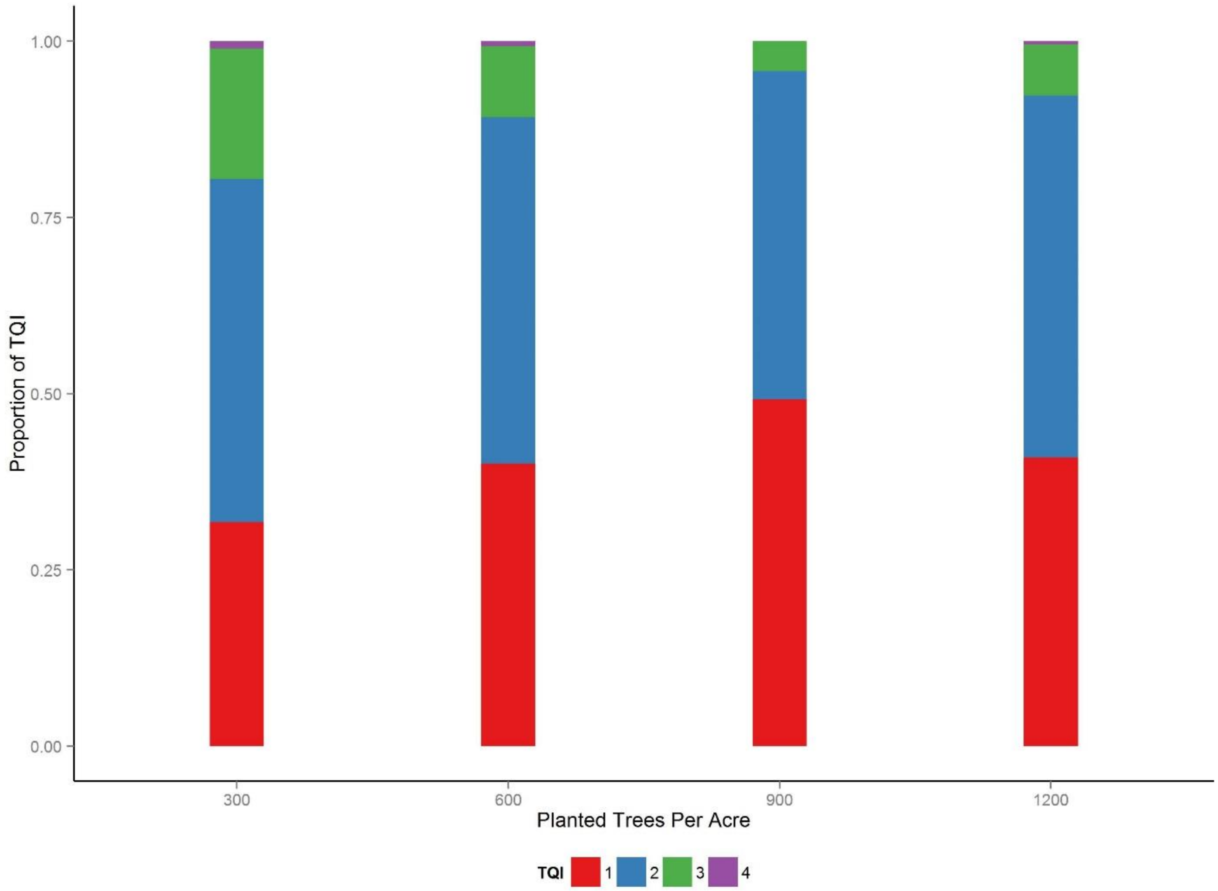

Figure 3.7: Proportion of TQI by planting density across all installations for PMRC SAGS Culture x Density thinned sites. The 600, 900, and 1200 tree per acre plots were thinned to the 300 TPA density at age 12 on Installations 3, 11, and 12 and age 10 at Installation 7.

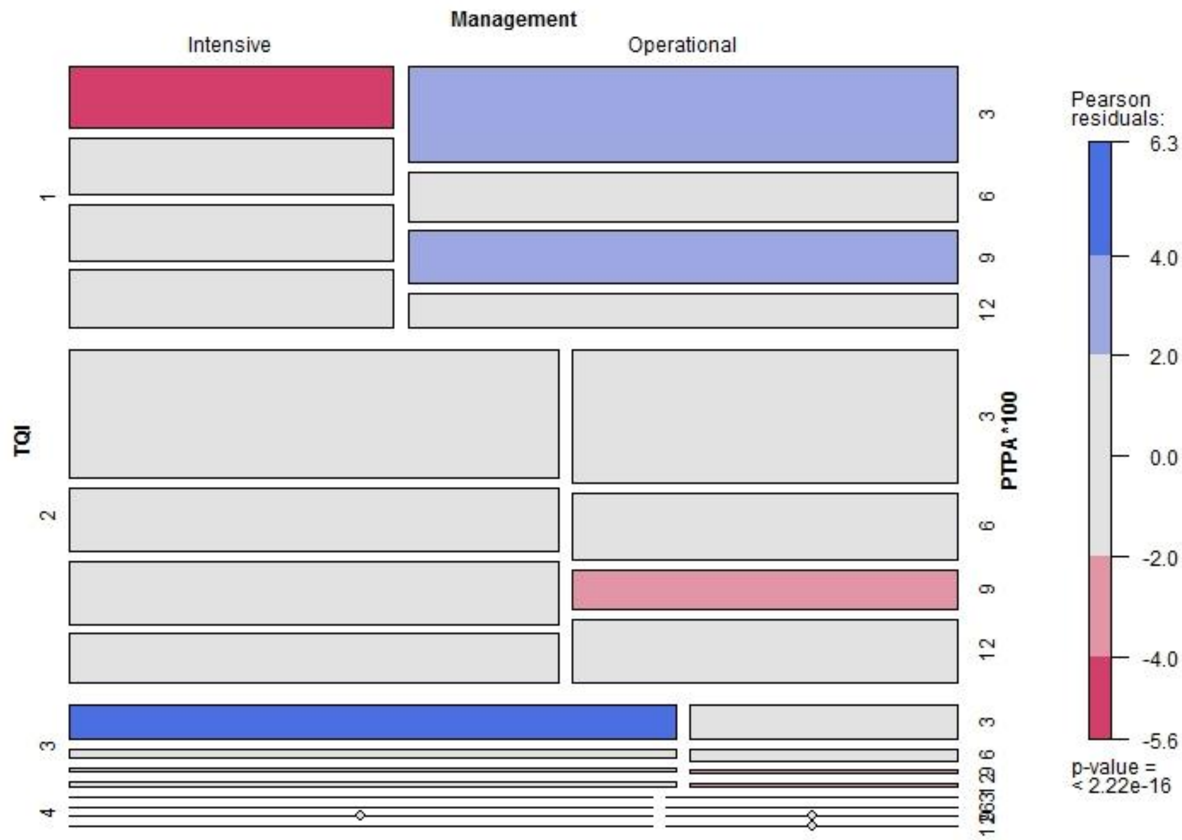

Figure 3.8: Comparison of trees across TQI scores for PMRC SAGS Culture x Density thinned installations. The height of the bars refers to planting density. The width of the bars refers to management intensity. The levels of the bars refer to the different TQI scores. When comparing density, the bars are similar in height, the densities are not significantly different. When comparing management, the bars are different in width, the management intensities are significantly different. The Pearson residuals refer to how significantly combinations of management intensity and planting density differ from expected counts of trees.

Figure 3.9: Comparison of trees with solid wood product potential for PMRC SAGS Culture x Density thinned installations. The height of the bars refers to planting density. The width of the bars refers to management intensity. The first level of bars are trees that do not exhibit solid wood potential while the lower bars are trees that do have solid wood potential. When comparing density, the bars are similar in height, the densities are not significantly different. When comparing management, the bars are different in width, the management intensities are significantly different. The Pearson residuals refer to how significantly combinations of management intensity and planting density differ from expected counts of trees.

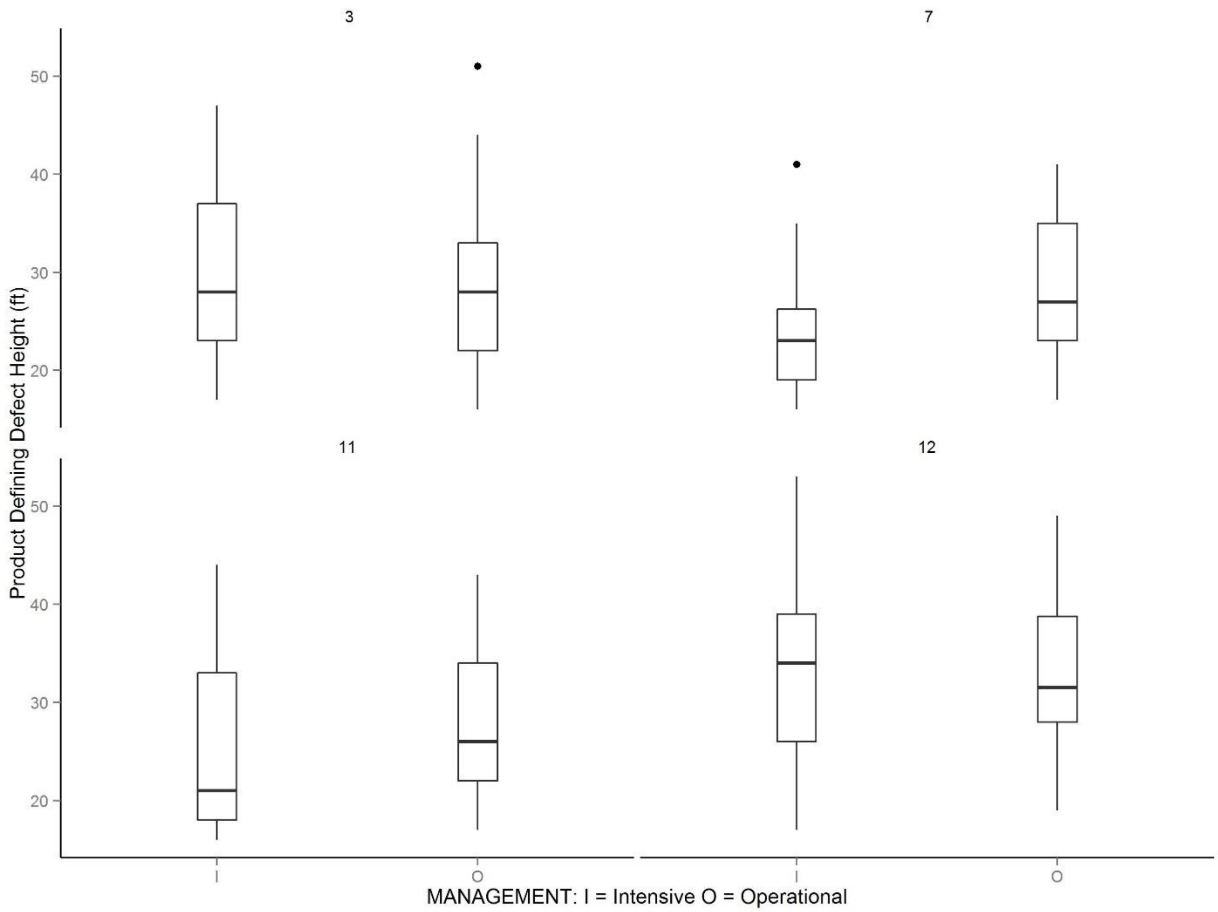

Figure 3.10: Product defining defect height by management intensity and installation for PMRC SAGS Culture x Density thinned sites.

.

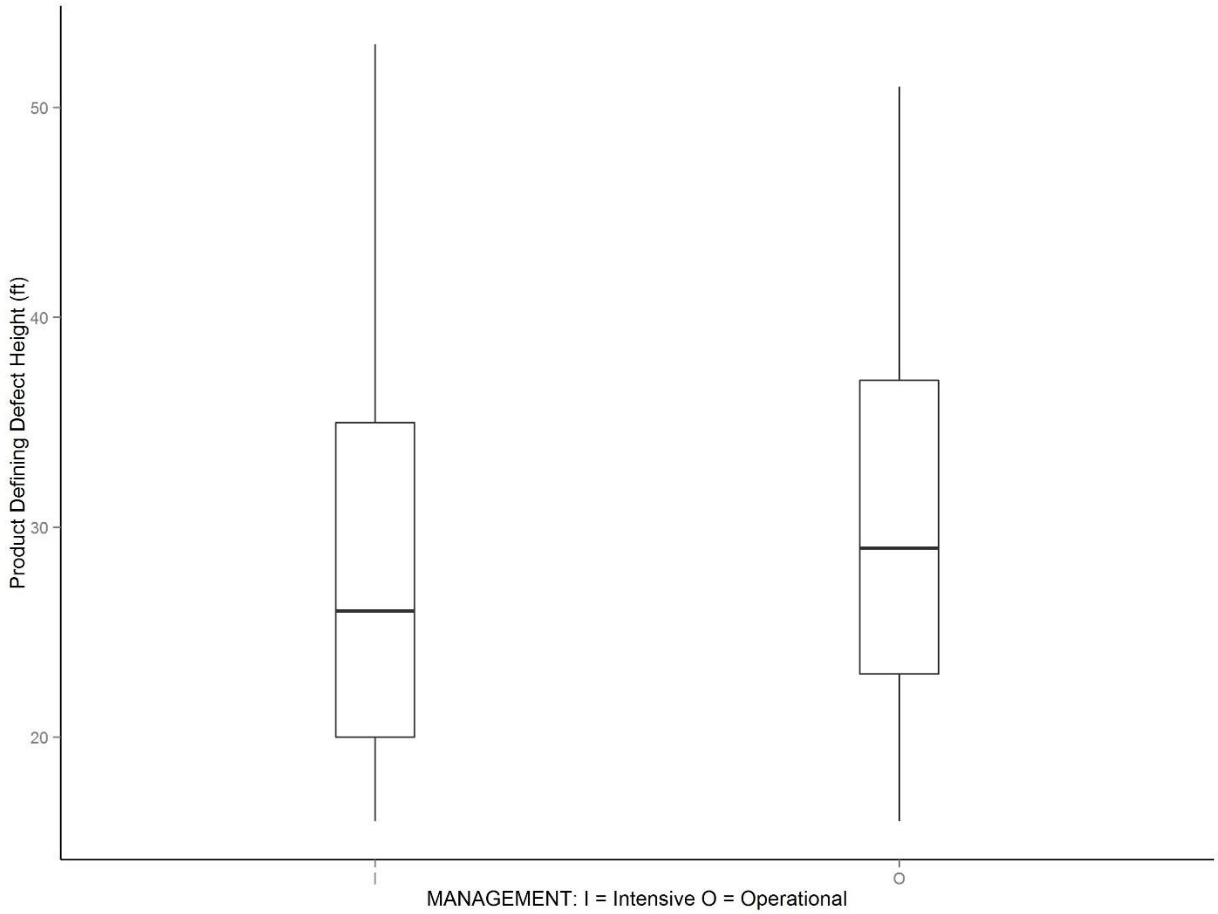

Figure 3.11: Product defining defect height by management intensity across installations for PMRC SAGS Culture x Density thinned sites.

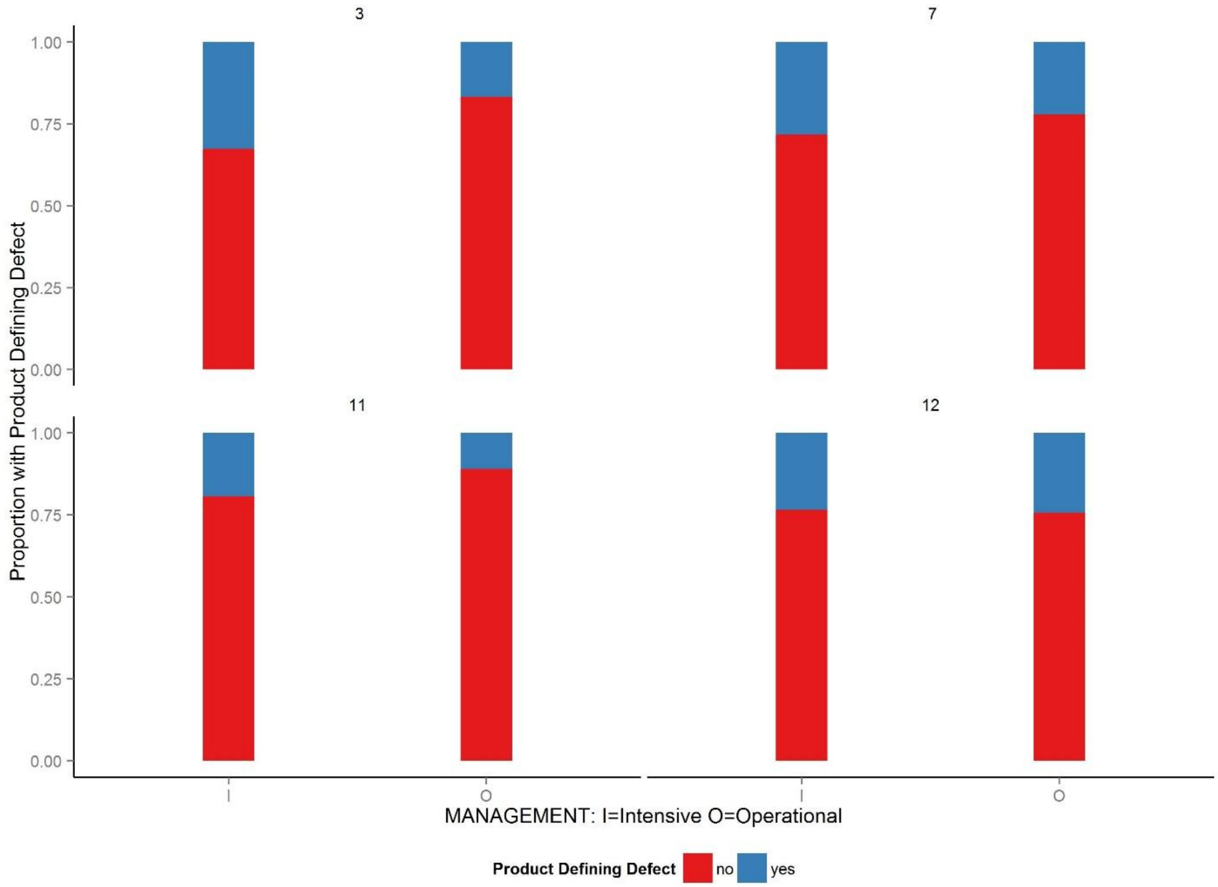

Figure 3.12: Proportion of stems with product defining defects by management intensity and installation for PMRC SAGS Culture x Density thinned sites.

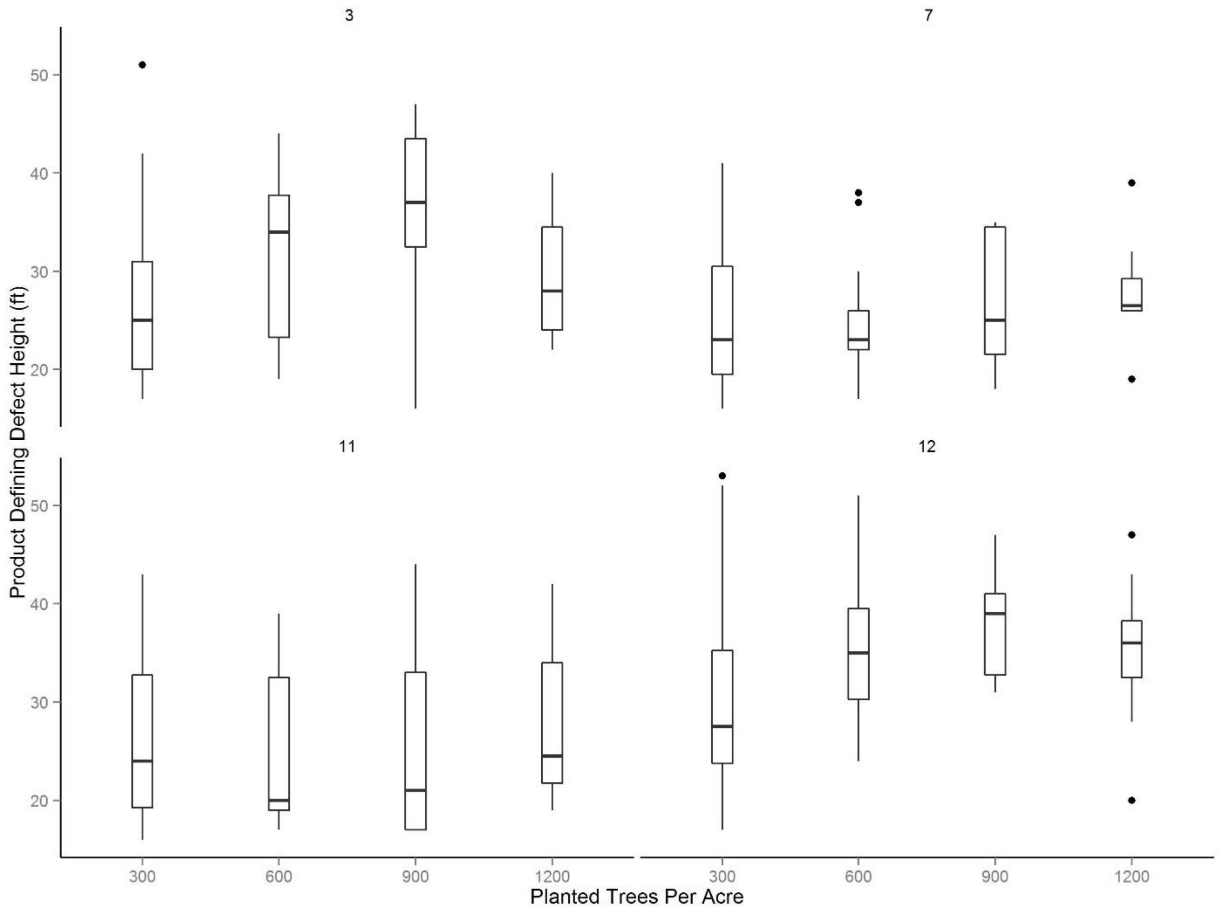

Figure 3.13: Product defining defect heights by planting density and installation for PMRC SAGS Culture x Density thinned sites. The 600, 900, and 1200 tree per acre plots were thinned to the 300 TPA density at age 12 on Installations 3, 11, and 12 and age 10 at Installation 7.

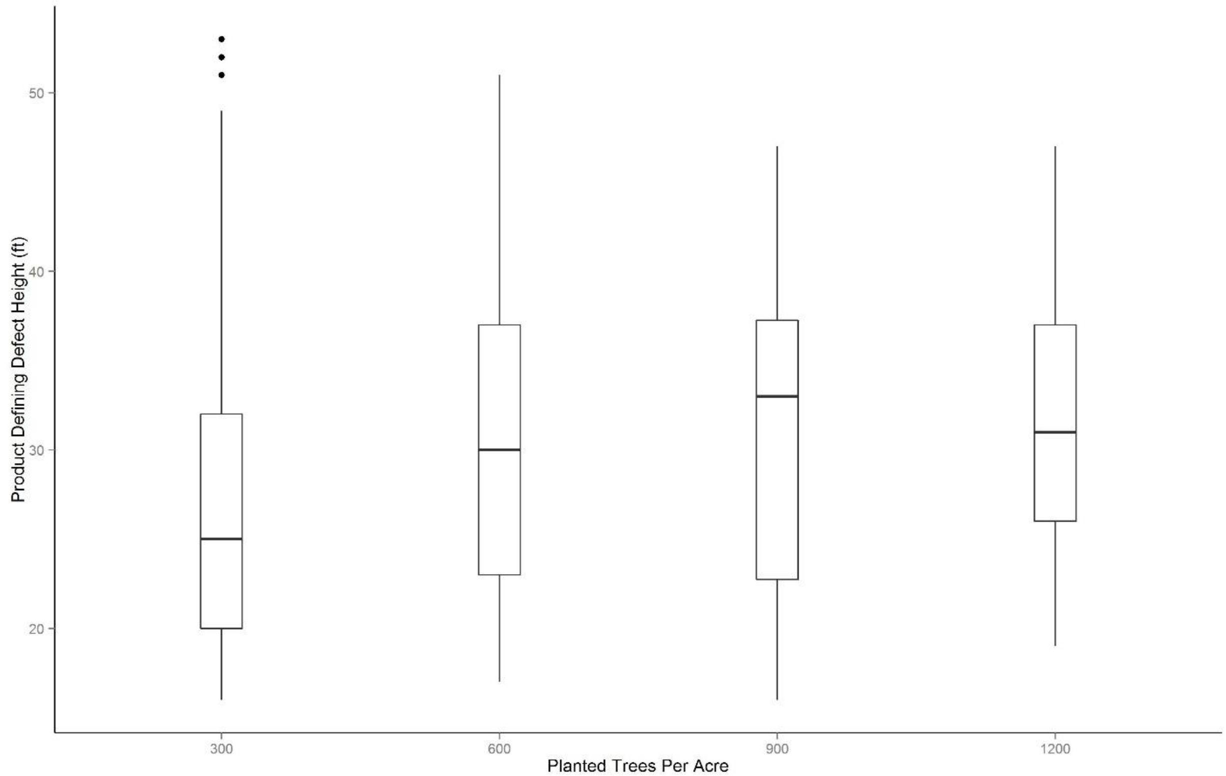

Figure 3.14: Product defining defect height by planting density across installations for PMRC SAGS Culture x Density thinned sites. The 600, 900, and 1200 tree per acre plots were thinned to the 300 TPA density at age 12 on Installations 3, 11, and 12 and age 10 at Installation 7.

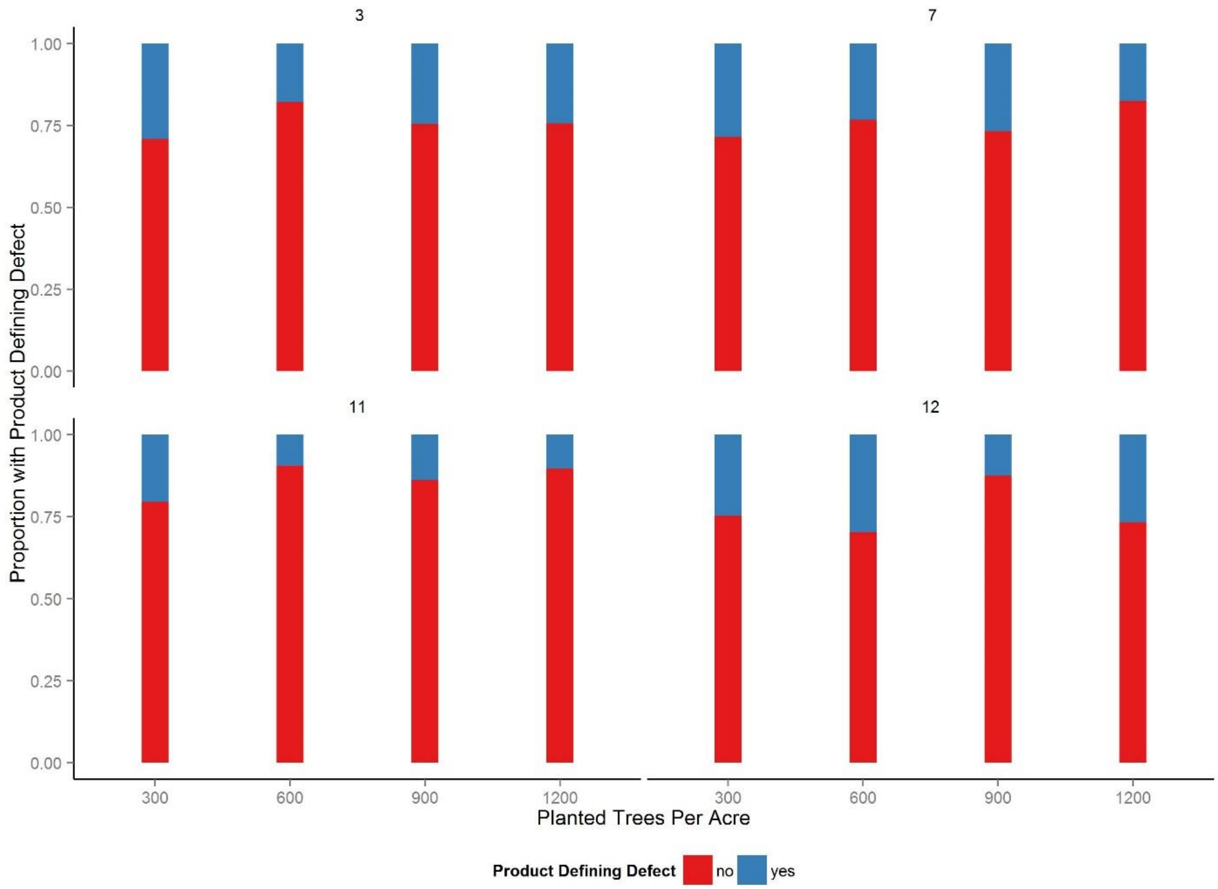

Figure 3.15: Proportion of stems with product defining defects by planted trees per acre and installation for PMRC SAGS Culture x Density thinned sites. The 600, 900, and 1200 tree per acre plots were thinned to the 300 TPA density at age 12 on Installations 3, 11, and 12 and age 10 at Installation 7.

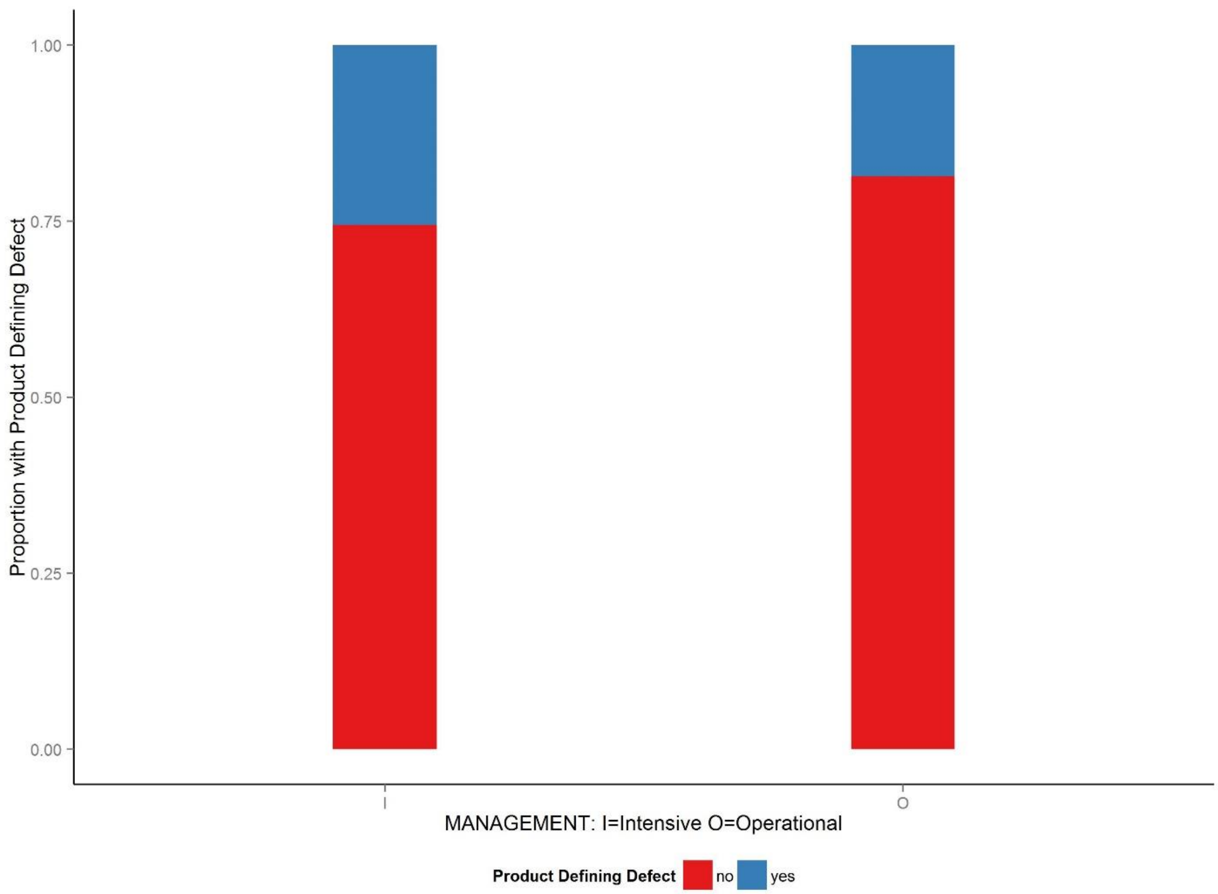

Figure 3.16: Proportion of stems with product defining defects by management intensity across all installations for PMRC SAGS Culture x Density thinned sites.

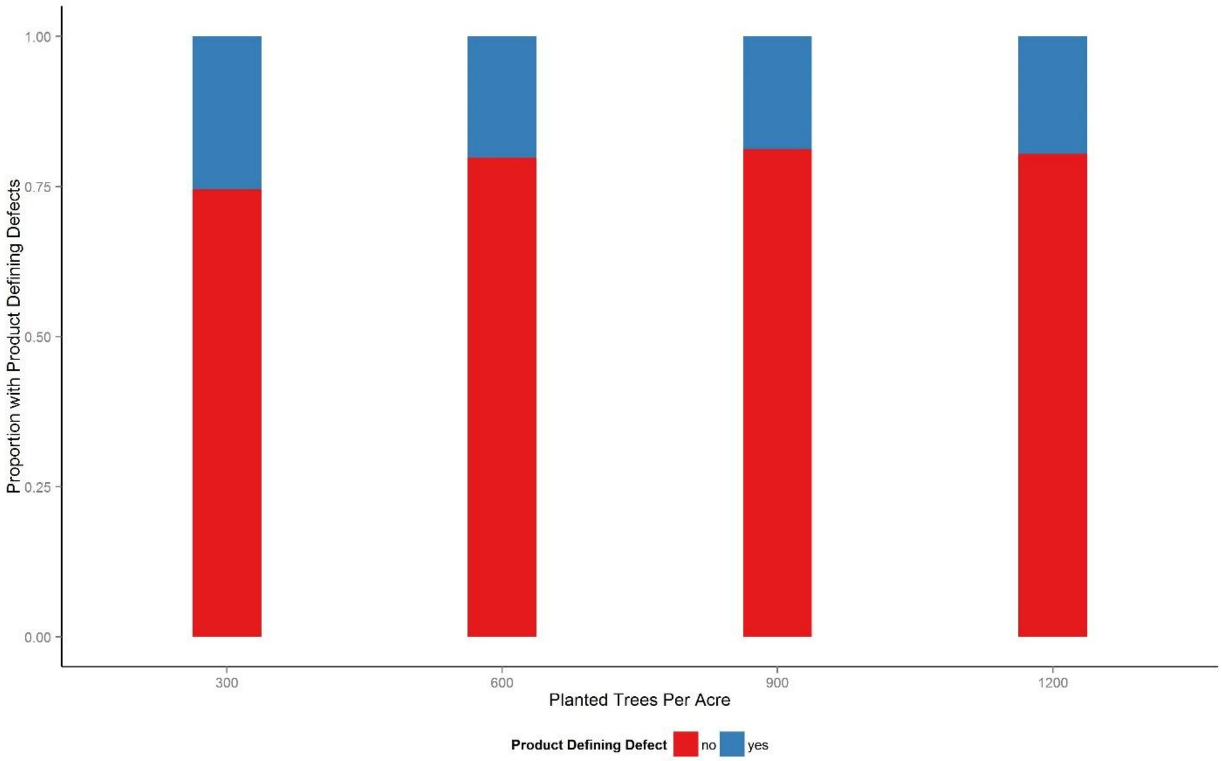

Figure 3.17: Proportion of stems with product defining defects by planting density across all installations for PMRC SAGS Culture x Density thinned sites. The 600, 900, and 1200 tree per acre plots were thinned to the 300 TPA density at age 12 on Installations 3, 11, and 12 and age 10 at Installation 7.

CHAPTER 4

COMPARISON OF PROPOSED TREE QUALITY INDEX (TQI) GRADING SYSTEM AND CURRENT PLANTATION MANAGEMENT RESEARCH COOPERATIVE (PMRC) TREE GRADING SYSTEM

Abstract

The proposed tree quality index (TQI) system and the current Plantation Management Research Cooperative (PMRC) tree grading system are compared. Results show that the PMRC grading system classifies a smaller proportion of stems that exhibit solid wood product potential than when using the TQI grading system. The PMRC and TQI systems showed similar trends in management intensity and density effects on tree quality. Intensive management was found to reduce overall tree quality. Increased planting density was found to decrease the proportion of stems with solid wood product potential.

Introduction

Methods for grading the stem quality of standing trees vary. Many are slow, complex, and realistically cannot be completed by field crews on large scale inventory projects. A Tree quality index (TQI) method was proposed for planted loblolly in East Texas (Tang et al. 1992). This TQI system includes a total of nine factors that are considered for each tree: diameter at breast height (DBH), total height (THT), height to live crown, crown class, single stem or multiple, straight stem crooked, single terminal leader or multiple terminal leaders, presence of stem cankers, and presence of branches with disease. Trees are scored on the presence of defects and requires recording a significant information for each tree. Each tree is given a TQI score which can range from as high as 36 to as low as 10. Another method for quickly determining if a tree has solid wood potential is to determine if a tree stem is straight enough that a line connecting the center of the stem and any two points, at least 16 feet apart, above the stump would not lie outside of the bole (Amateis and Burkhart 2005). Grading immature trees has proven to be a difficult task to accomplish in the field. A grading system for non-merchantable loblolly pine trees was developed into a key format for field foresters (Belli et al. 1997). This is a complicated, time consuming process that has a high potential for error due to its complexities. When implemented correctly, it serves as a useful guide to grade immature loblolly pine. Cylindrical form factor (CFF) is another method used to describe stem form in southern pines. The CFF is defined as the ratio of tree volume to the volume of a cylinder of the same height. The CFF effectively characterizes the effects of fertilization on stem form (Jokela et al. 1989). A method to grade standing trees was used in two studies by Cumbie et al. (2012) and Norman (2014). In these studies, a score of 1 indicated a high quality crop tree with no defects in the first 24 feet. A score of 2 indicated a crop tree with minor defects and no forks or other major defects below 16 feet. A score of 3 indicated that the tree contains defects that will limit any solid wood product potential. A score of 4 indicated a cull tree. The Plantation Management Research Cooperative (PMRC) employs a tree grading system in its routine measurements of field studies throughout the U.S. South. This grading system is designed to not only grade a tree's product potential, but to also assess any damage, disease, or other possible stem and crown issues.

The proposed TQI system is a method to grade trees that uses a 1 to 4 classification that classifies stems based on their potential to produce solid wood products. This system is consistent, easy to teach, and provides reliable information regarding overall tree quality in a stand.

The present chapter has the objectives of: (1) Clearly defining the Tree Quality Index (TQI) system and the Plantation Management Research Cooperative (PMRC) tree grading system. (2) Compare the results between the two methods and (3), Identify strengths and weaknesses of the two systems and provide recommendations for grading standing trees. The comparison of the two methods will allow for both verification of the results found is Chapter 2 and Chapter 3 of this present research and also to compare two methods of grading tree quality.

Hypothesis

1. The TQI system will provide comparable stand level tree quality information to the current PMRC standing tree grading method.
2. The PMRC grading system and the TQI grading system will result in similar conclusions regarding the effects of management intensity and planting density on stem quality.

Methods and Materials

The Plantation Management Research Cooperative installed the South Atlantic Gulf Slope (SAGS) Culture x Density Study across the Piedmont and Upper Coastal Plain of the southern United States in 1998 and 1999. The study examined six loblolly pine planting densities of 300, 600, 900, 1200, 1500, and 1800 trees per acre. Each installation consisted of two different management intensities (Table 4.1). In the 16th growing season, additional quality assessments were conducted on six non-thinned installations (Table 4.2), distributed across the range of the study (Figure 4.1). The additional quality assessments were conducted on the 300, 600, and 900 tree per acre subplots. Each planting density plot varied in size as did the measurement plot contained within the subplot (Table 4.3). Measurement plots were surrounded by an approximately 26 ft. wide buffer to eliminate possible edge effects

The proposed TQI system is a 1-4 scale. Quality scores are ordinal, categorical variables. While the TQI system has a degree of subjectivity, it is a fast, easy to implement, and easy to modify method for grading standing trees. The specifications used in this study are shown in (Table 4.4). Accurate measurement and recording the height to the nearest foot of product defining defects is a very important component of the TQI system. This is accomplished most efficiently in the field through the use of a laser hypsometer. The TQI system scores tree product potential, not necessarily current product.

The tree grading system currently used by the Plantation Management Research Cooperative (PMRC), utilizes a set of codes in four categories to grade trees. The PMRC tree grading system is shown in (Table 4.5). The PMRC grading system collects detailed information regarding defects on trees however it is lacking in several categories. While product defining defects are acknowledged, their height on the stem are not measured. This is in contrast to the TQI system.

Analysis

All analysis conducted for this research was conducted using the R statistical package (R Core Team 2014). All graphics were developed using the packages ggplot2 (Wickham 2009).

Comparison between the PMRC tree grading system and the TQI system includes comparing proportions of stems that exhibit solid wood product potential. For the purposes of this comparison, the TQI system was examined in a binary format in which stems graded TQI 1 or 2 exhibit solid wood product potential and stems graded TQI 3 or 4 do not exhibit solid wood product potential. The PMRC system was transformed into a binary format in which only stems graded with solid wood product potential code of 0, (Table 4.5), exhibit solid wood product potential. Analysis compared totals of stems that exhibit solid wood potential for both systems across management intensities and planting densities. Comparisons were made to determine if similar conclusions can be drawn about the effects of management intensity and planting density regardless of grading system. All comparisons were on the same non-thinned installations in the PMRC SAGS Culture x Density study examined in Chapter 2.

Results

Comparisons between the two methods show differences in stems determined to have solid wood product potential. The PMRC grading resulted in a much greater portion of stems that do not exhibit solid wood product potential. This is true across both management intensities and all planting densities (Table 4.6). When the effects of management intensity and planting density on tree quality were analyzed using both systems, similar results were found. When intensive management is compared with operational management, the intensive culture resulted in fewer stems with solid wood product potential for the PMRC (Figure 4.2) and the TQI systems (Figure 4.4). Unlike the TQI system (Figure 4.5), an apparent decrease in tree quality was observed using the PMRC grading system as planting density increases (Figure 4.3). The difference in solid wood product potential proportions between cultures was statistically significant at $\alpha=0.05$ level using the PMRC (Table 4.7) and the TQI grading systems (Table 4.9). The difference in solid wood product potential proportions among the three planting densities was significantly lower at $\alpha=0.05$ level as density increased using the PMRC grading system (Table 4.8) but not significantly different at $\alpha=0.05$ level using the TQI grading system (Table 4.10).

Discussion

Both the TQI system and the PMRC system are improvements over not recording any tree quality information. Tree quality is a significant driver in the valuation of a stand. Not having this information limits the ability to properly manage timber (Tang et al. 1992). Both the TQI system and the PMRC system provide valuable information that can be used to better merchandize a stand and to better predict and project future product yields. It is common to assume a downgrade percentage for stems large enough to produce solid wood products, however, as with every biological system, there is a large amount of variation among stands in the proportions of stems that exhibit potential for higher valued wood products.

Acknowledged limitations exist with the proposed TQI system. The largest limitation with this system is that the quality assessments have a degree of subjectivity. While there are set rules for assigning a tree quality score, it would be unusual for two independent technicians to grade every tree in a stand exactly the same. Further, the TQI system grades tree product potential. It can be challenging to grade certain tree’s potential product especially when the stem is pre-merchantable. While this work presents its flexibility as an advantage, comparisons among stands that were graded with different TQI specifications are often difficult.

Limitations exist with the current PMRC grading system. The largest limitation with this system is that product defining defect heights are not measured. This lack of information limits the ability to accurately merchandize a stand. The PMRC system utilizes four different sets of codes with options within each set. The detailed PMRC assessment requires more time to complete than the more general TQI method. When efficiency goals must be met, field personnel will lose valuable time using such a detailed system. Another limitation of the PMRC grading system is that defects in the butt log automatically degrade the tree to have no solid wood product potential. While this is often true, the ability to measure these defects also known as "jump-butts", more realistically represents how stems are merchandized in operational timber harvesting. The final limitation to this method is that information can be lost due to the structure of the tree grading codes. For example, if a tree is in the dominant crown position and is also leaning, the technician may only record that the tree is leaning using the code structure. Losing the crown class is important information that is lost due to the code structure. The grading system used by the PMRC is not specifically designed for classifying merchantability. The system was designed for describing defects on an individual tree regardless if they have a direct influence on tree product potential. While there are limitations, more detailed conclusions can be made with the PMRC system with its additional levels of information collected.

There were significant differences in proportions of stems found to exhibit solid wood potential using the PMRC and the TQI systems. If the PMRC system is deemed to under-classify the number of stems with solid wood product potential, the counts of potential stems can be adjusted with a ratio to be similar to the TQI system. In a similar manner, if the TQI system is deemed to over-classify the number of stems with solid wood product potential, it can be adjusted to more closely reflect the PMRC grading system. The amount of legacy information that the PMRC system provides is substantial and being able to utilize this data could be used to conduct further product potential research. A major driver for the differences in the TQI grading system and the PMRC system is that the PMRC grading procedure only evaluates potential for sawtimber, not other solid wood products. The TQI system evaluated a stem's potential for all solid wood products including super-pulp, chip and saw, sawtimber, and others. Sawtimber, being one of the highest value solid wood products, has stricter quality requirements than lower valued products.

While the two measurement systems do appear to have significant differences, it is interesting that the conclusions on the influence of planting density and management intensity appear to be comparable regardless of the grading system used. Both the PMRC and the TQI grading systems indicated that operational management produces higher proportions of stems with solid wood product potential than intensive management (Figure 4.2 and Figure 4.4). There is evidence to suggest that the PMRC grading system concludes that as planting density increases, the proportions of stems with sawtimber potential decreases (Figure 4.3). This result is significant at α=0.05 level (Table 4.8). This is a surprising result as it is commonly assumed that higher planting density improves "average" tree form in a stand. Prior work in this study in Chapter 2 concluded that there was no significant difference (Table 4.5) however there was a slight trend downward in proportion of stems that exhibit solid wood product potential decreases as density increases (Figure 4.10). It is well known that at lower densities, average branch size increases and self-pruning occurs later in the stems lifespan, however, long term studies on product potential for lower planting densities are not available.

Every tree grading system has subjectivity, however, to actually know which is the more accurate system, a mill study would have to follow in which trees are actually utilized for product. If one grading method is determined to be more accurate, the other can be adjusted to better reflect how trees are utilized in a particular area. It is important that tree quality evaluations should be an adaptable measure. Different markets have different specifications for tree quality when producing a product. For the purposes of tree quality research, a standard method should be developed in which comparisons are more meaningful.

Conclusions

A limitation with any tree grading system is subjectivity. Every grading system has some degree of subjectivity that cannot be avoided. The key with any system chosen is to be as consistent as possible and have clear rules that limit subjectivity. Further, training field technicians on how to grade trees helps ensure better consistency among measurements. It is clear that the PMRC method grades stems differently than the TQI method.

The PMRC system predicted far fewer trees with solid wood potential than did the TQI system. This is due to the differences in grading approaches such as the solid wood product that the grading specifies.

It is encouraging that the two grading systems showed the same trends for the effects of management intensity and planting density. The trend that intensive management reduces overall tree quality in a stand was clear for both grading systems. The PMRC system noted the trend that tree quality decreases as planting density increases. While the trend with the TQI system was apparent, it was not a statistically significant and was much more pronounced with the PMRC system. Further research needs to be conducted to make conclusions regarding planting densities effect on tree quality.

The PMRC system does not measure product defining defect heights. It is the opinion of the author that this is a very valuable measurement and should be added to the PMRC system.

The TQI system provides comparable, and in some ways improved, tree quality information, as compared with the PMRC grading system. While a time study was not conducted to determine the speed of grading, by casual observation, the TQI grading system is at least as fast as the PMRC grading system. The time needed for measuring the height of product defining defects is greatly minimized through the use of a laser hypsometer making this measurement minimally time consuming.

Literature Cited

Amateis, R. L., and Burkhart, H. E. 2005. The influence of thinning on the proportion of peeler, sawtimber, and pulpwood trees in loblolly pine plantations. Southern Journal of Applied Forestry 29(3): 158-162.

Belli, K. L., Land Jr, S. B., and Duzan Jr., H. W. 1997. A tree quality scoring system for immature loblolly pine. Southern Journal of Applied Forestry 21(1): 24-27.

Cumbie, W. P., Isik, F., and McKeand, S. E. 2012. Genetic improvement of sawtimber potential in loblolly pine. Forest Science 58(2): 168-177.

Jokela, E. J., Harding, R. B., and Nowak, C. A. 1989. Long-term effects of fertilization on stem form, growth relations, and yield estimates of slash pine. Forest Science 35(3): 832-842.

Norman, T. B. 2014. Impacts on growth and quality of interplanting loblolly pine (*Pinus taeda* L.) seedlings with clonal material in the Lower Coastal Plain of North Carolina. M.S. Thesis, North Carolina State University Department of Forestry and Enviromental Resources. Raleigh. NC. 116 pp.

R Core Team 2014. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Tang, D., Lenhart, J. D., and Kronrad, G. D. 1992. Development of a provisional tree quality index for planted loblolly pines in east Texas. Southern Journal of Applied Forestry 16: 106-110.

Wickham, H. 2009. ggplot2: Elegant graphics for data analysis. Springer, New York.

Tables and Figures

Table 4.1: Detail of cultural regimes utilized in PMRC SAGS Culture x 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: 500 lbs/ac 10-10-10 Before year 8: 200 lbs/ac N + 25 lbs/ac P Before year 12: 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 Before year 10: 200 lbs/ac N + 25 lbs/ac P Before year 12: 200 lbs/ac N + 25 lbs/ac P Before year 14: 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

Table 4.2: Geographic details, soil details, and site quality for PMRC SAGS Culture x Density non-thinned installation utilized.

Installation	County	State	Physiographic Province	NRCS Soil Series	Soil Taxonomy	Site Index*
5	Talbot	GA	Piedmont	Lloyd	Fine, kaolinitic, thermic Rhodic Kanhapludults	89
6	Marion	GA	Upper Coastal Plain	Lakeland	Thermic, coated Typic Quartzipsamments	69
13	Jasper	GA	Piedmont	Lloyd - Pacolet	Fine, kaolinitic, thermic Rhodic Kanhapludults	84
16	St. Clair	AL	Piedmont	Conasauga and Firestone	Very-fine, mixed, active, thermic Chromic Vertic Hapludalfs	71
17	Harolson	GA	Piedmont	Grover	Fine-loamy, micaceous, thermic Typic Hapludults	84
18	Chatooga	GA	Piedmont	Fullerton	Fine, smectitic, thermic Vertic Paleudalfs	75

*Site index is shown for operational culture planted at 600 trees per acre base age 25.

Table 4.3: Planting density plot sizes for PMRC SAGS Culture x Density study.

Planting Density (TPA)	Spacing (ft. x ft.)	Trees per measure plot	Measure plot size (ac)	Gross plot size (ac)
1800	6 x 4	184	0.1	0.31
1500	6 x 4.8	160	0.11	0.32
1200	6 x 6	120	0.1	0.3
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

Table 4.4: Tree Quality Index (TQI), specifications utilized for grading standing trees in the PMRC SAGS Culture x Density study.

TQI Classes	Specifications
1	No defects that will limit solid wood potential. No product defining defects below 48 feet.
2	Moderate defects that will limit solid wood potential. No product defining defects below 16 feet.
3	Major defects that eliminate solid wood potential. Pulpwood forever.
4	Serious defects that eliminate all merchantability. Cull.

* For trees below 48 feet any product defining defect present on stem will automatically disqualify stem from being scored a TQI 1.
** A product defining defect is defined as a defect present on the stem that will eliminate solid wood product potential past the defect.

Table 4.5: Plantation Management Research Cooperative tree grading system. The “solid wood product potential” codes were compared against the Tree Quality Index (TQI).

Crown Class Codes	Solid Wood Product Potential	Cronartium Codes	Damage Codes
1 = dom/codom	0 = no defects	0 = no infection	0 = none
2 = intermediate	1 = reject for 1st log fork	1 = 1 to 25 %	1 = yellow needles
3 = suppressed	2 = reject crook/sweep	2 = 26 to 50 %	2 = dead needles
4 = wildling	3 = reject for cronartium	3 = 51 to 75 %	3 = tip dieback
5 = broken top		4 = 76 to 100 %	4 = wildling
6 = leaning tree			5 = broken top
7 = broken stem			6 = leaning tree
8 = insect damage			7 = broken stem
			8 = insects
			9 = cut
			10 = forked stem

Table 4.6: Comparison of percentage of stems with solid wood product potential between PMRC tree grading and TQI tree grading methods.

Management	Planted Trees Per Acre	PMRC Percent Solid Wood Potential	TQI Percent Solid Wood Potential
Intensive	300	40.0	81.8
Intensive	600	39.6	79.6
Intensive	900	32.8	76.4
Operational	300	58.2	92.1
Operational	600	50.3	91.7
Operational	900	48.6	88.3

Table 4.7: Two sample proportion test comparing proportion of stems without solid wood product potential between two levels of culture, graded using the PMRC tree grading system for the non-thinned SAGS Culture x Density study.

2-sample test for equality of proportions	
Chi-squared = 61.26, df = 1, p-value =0.000	
Prop 1 (int. man.)	prop 2 (op. man.)
0.626	0.477

Table 4.8: Three sample proportion test comparing proportion of stems without solid wood product potential between three planting densities, graded using the PMRC tree grading system for the non-thinned SAGS Culture x Density study.

3-sample test for equality of proportions without continuity correction		
Chi-squared = 12.53, df = 2, p-value = 0.002		
prop 1 (300 tpa.)	prop 2 (600 tpa.)	prop 3 (900 tpa)
0.51	0.55	0.59

Table 4.9: Two sample proportion test comparing proportion of stems with solid wood product potential between two levels of culture, graded using the TQI tree grading system for the non-thinned SAGS Culture x Density study.

2-sample test for equality of proportions	
Chi-squared = 65.096, df = 1, p-value = 0.000	
prop 1 (int. man.)	prop 2 (op. man.)
0.79	0.9

Table 4.10: Three sample proportion test comparing proportion of stems with solid wood product potential between three planting densities, graded using the TQI tree grading system for the non-thinned SAGS Culture x Density study.

3-sample test for equality of proportions without continuity correction		
Chi-squared = 5.57, df = 2, p-value = 0.062		
prop 1 (300 tpa.)	prop 2 (600 tpa.)	prop 3 (900 tpa.)
0.86	0.86	0.83

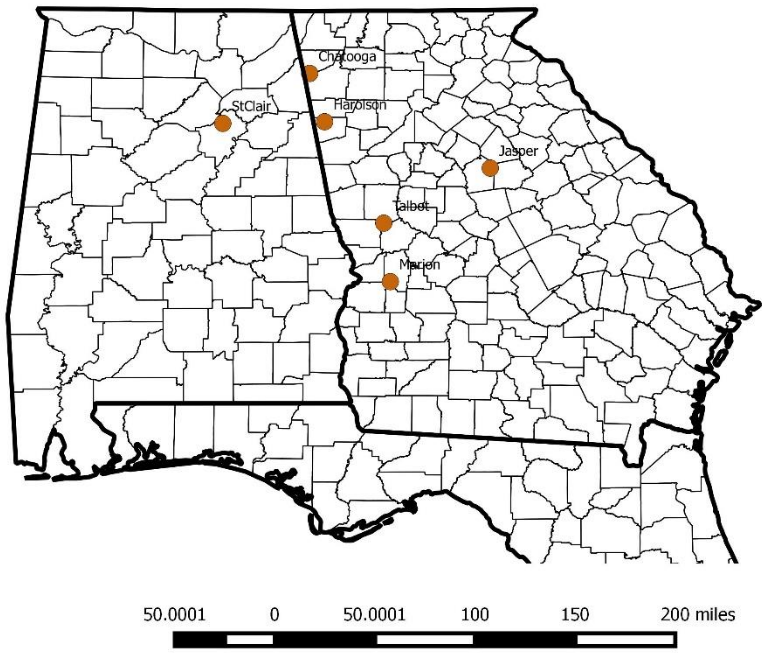

Figure 4.1: Non-thinned PMRC SAGS Culture x Density Study Sites Evaluated.

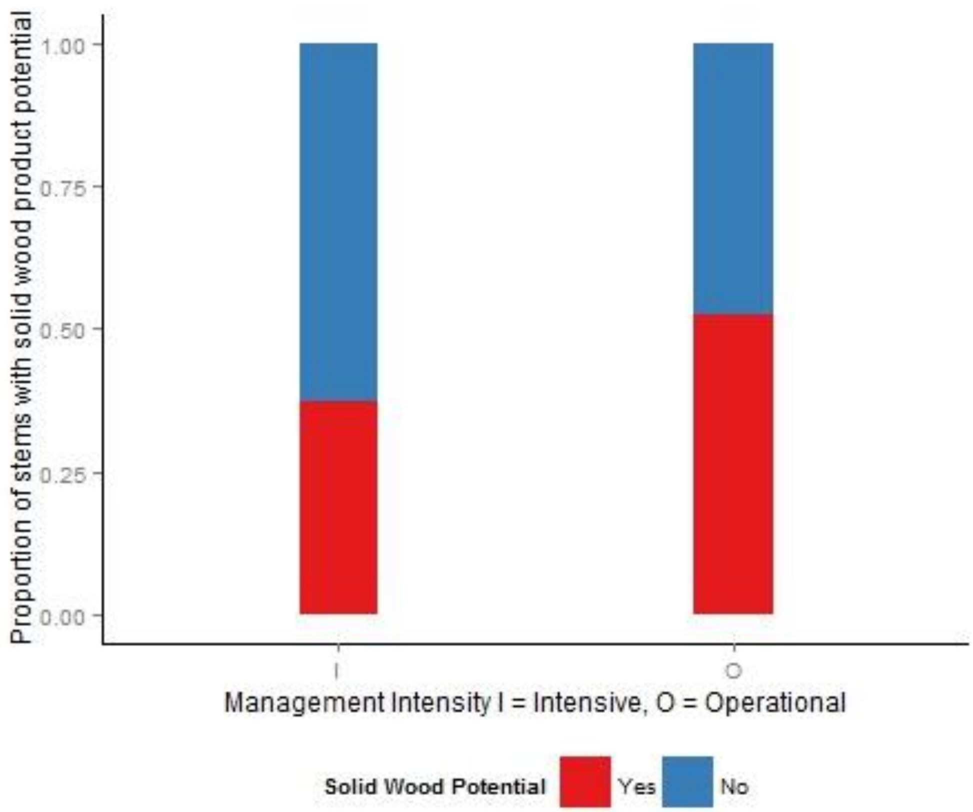

Figure 4.2: Solid wood product potential proportion comparison between culture levels graded with the PMRC tree grading system on non-thinned PMRC SAGS Culture x Density sites.

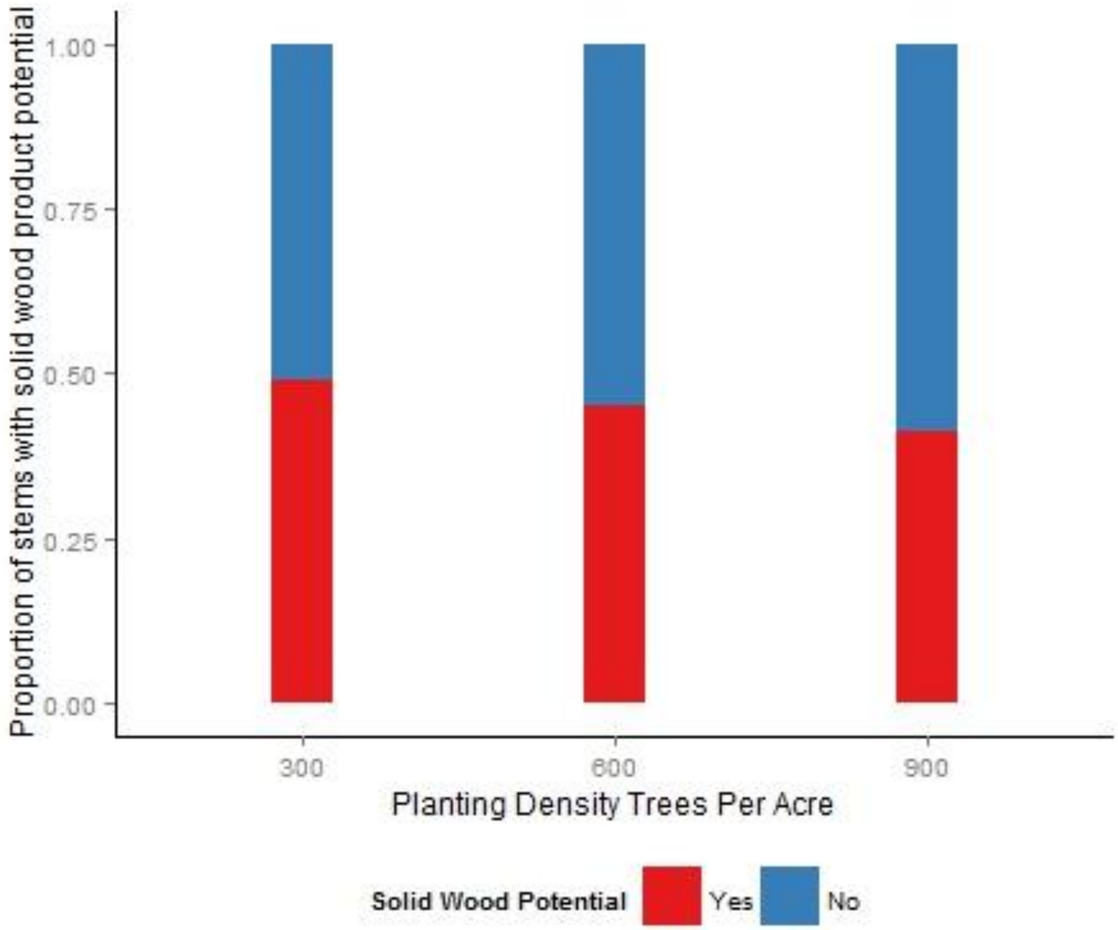

Figure 4.3: Solid wood product potential proportion comparison between planting densities graded with the PMRC tree grading system on non-thinned PMRC SAGS Culture x Density sites.

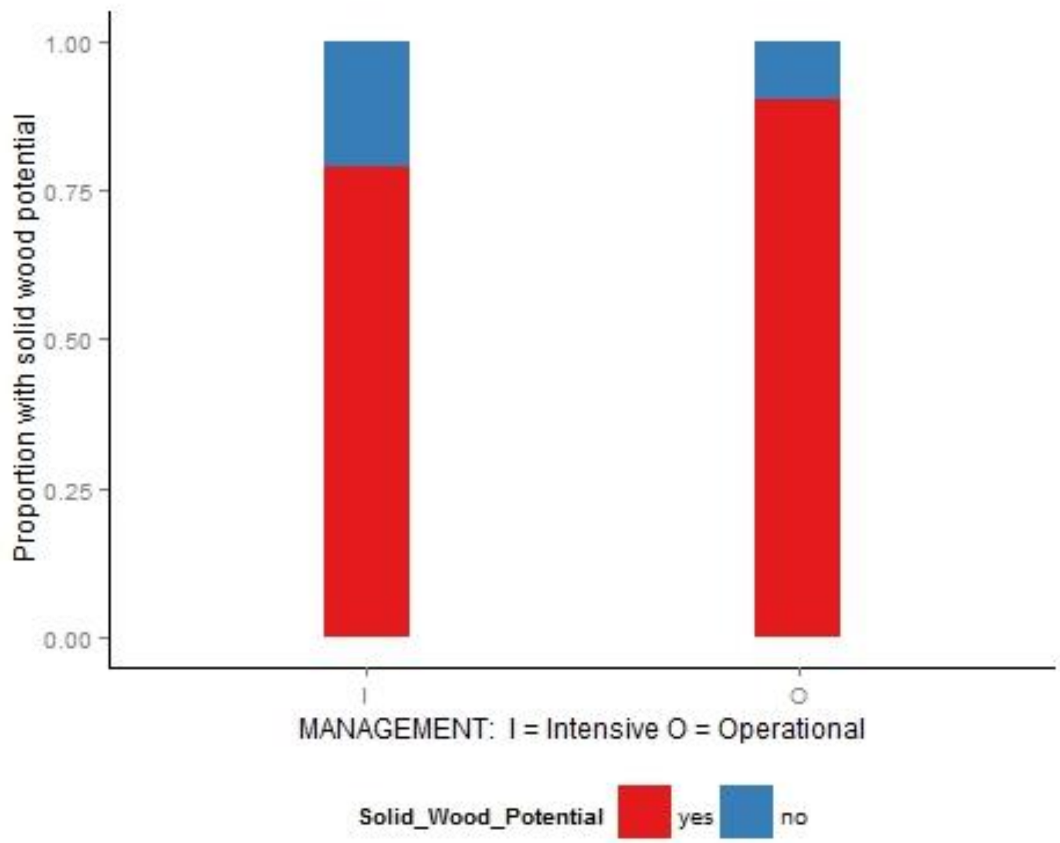

Figure 4.4: Solid wood product potential proportion comparison between two culture levels graded with the TQI tree grading system (viewed in binary yes, no format) on non-thinned PMRC SAGS Culture x Density sites.

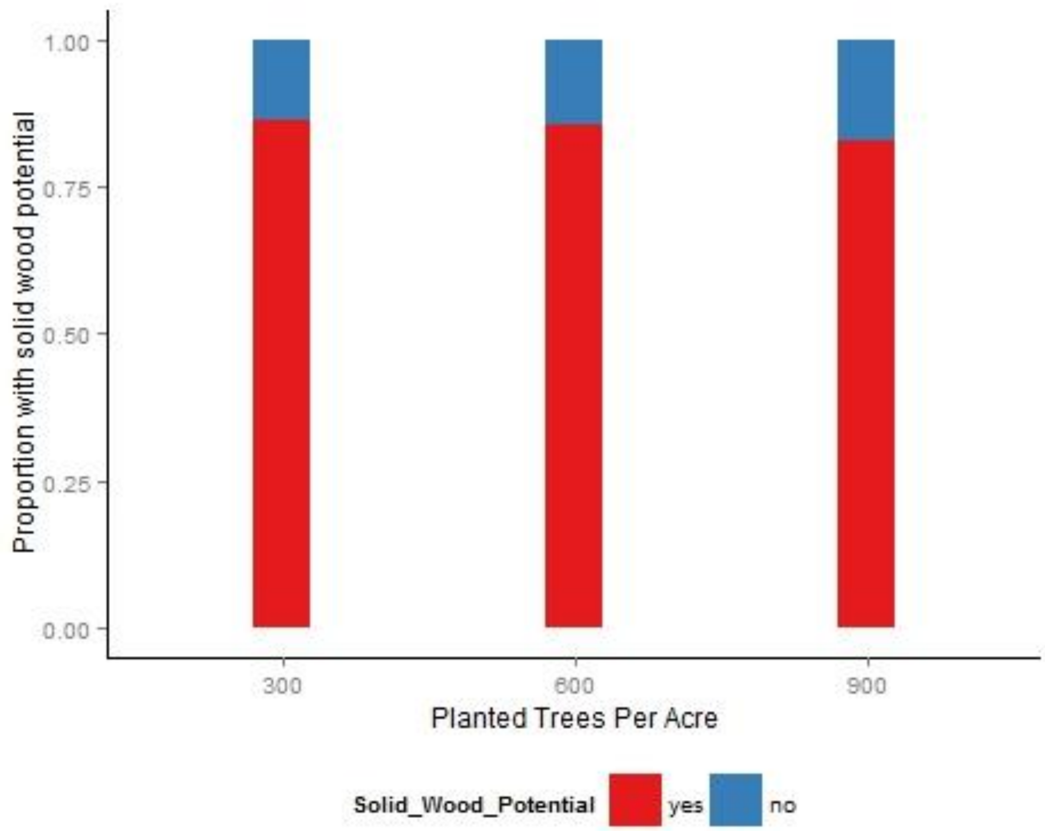

Figure 4.5: Solid wood product potential proportion comparison between planting densities graded with the TQI tree grading system (viewed in binary yes, no format) on non-thinned PMRC SAGS Culture x Density sites.

CHAPTER 5

CONCLUSIONS

Ten installations of the Plantation Management Research Cooperative's South Atlantic Gulf Slope Culture x Density study were utilized to evaluate the effects of management intensity and planting density on tree quality. Six installations evaluated were non-thinned plantations and four installations evaluated had plots previously thinned. At non-thinned installations, both operational and intensive culture were examined at three initial planting densities of 300, 600, and 900 trees per acre. At thinned installations, both operational and intensive culture were examined at four initial planting densities of 300, 600, 900, and 1200 trees per acre where the 600, 900, and 1200 planting densities were thinned. Every live tree on these installations were examined in either their 15th or 16th growing season depending on establishment year. Quality assessments were carried out using a Tree Quality Index (TQI) grading system. Every tree received a TQI assessment that judged the stem's solid wood product potential and the stem height to a product defining defect (e.g. forking, broken top, disease canker, etc.), where present, was measured to the nearest foot.

In non-thinned stands, management intensity was a more significant factor of tree quality than was planting density. Intensive management reduced tree quality compared with operational management. There were no significant differences in proportions of stems with solid wood product potential between the planting densities. Thinned stands exhibited higher overall stem quality than did non-thinned stands. Intensive management reduced tree quality compared with operational management in thinned stands as well as non-thinned stands.

A comparison was carried out between the TQI grading system and the currently employed PMRC tree grading system on the non-thinned installations. Significant differences were observed between the two systems for the proportions of stems exhibiting solid wood product potential among the three planting densities and between the two levels of management intensity. While the proportions were found to be very different, conclusions about the effects of management intensity on tree quality were the same in that intensive culture reduced overall tree quality. The PMRC grading system found that the proportion of stems with solid wood product potential decreased with greater planting density. The TQI method found a similar trend, however unlike the PMRC system result, this trend was not significant.